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I beg to submit —

An original design for a Resistance Box, planned with a view to the reduction of the temperature error, — with all necessary experimental data;

Also notes on original improvements upon existing methods of winding, jointing and ventilating resistance coils.

— This report is accompanied by a full-size model made according to this design, showing the saving in first cost and the diminution of weight and bulk accomplished.
Outline.

The following report comprises a discussion of existing forms of resistance boxes; their principal sources of error, and various means by which these errors may be reduced; and includes original designs made with a view to eliminating or reducing these errors, more especially the error introduced into the value of the resistance coils by a deviation from the temperature at which these coils were standardized and adjusted; and comprises also further notes and plans for simplifying existing methods of constructing resistance boxes, with a view to cheapening the process and reducing the bulk and weight of the apparatus...
One of the most important standards of measurement in electrical work is the standard of resistance. Coils of wire, carefully adjusted to equality with coils whose resistance is taken as standard, or with exact multiples of these standards—are grouped together in boxes, called resistance boxes, and upon the accuracy with which the ohmic value of these coils is determinable, depends the accuracy of almost all electrical testing.

A multiplicity of designs of resistance boxes exists, but all those in practical use now, consist essentially of coils of insulated wire contained in a closed box, stamped with the resistance-values which the coils possessed at the time of their adjustment.
which was made at a certain stipulated temperature.

The terminals of each coil are brought up through the top of the box, and fastened to heavy brass blocks firmly set in some good insulating material. In order that the total resistance of the box shall be as nearly as possible that of the coils alone, the utmost care is exercised in making these terminal blocks and connecting pieces of low resistance.

These resistance coils are wound generally in close-lying layers, on small spools of insulating material; the passage through the coiled wire of an electric current causes the mass of the wire, a greater or less heating effect. The heat thus generated cannot escape freely because of
the compact winding of the coil. The resistance of the metal or alloy, of which the wire used in the coils is made, is in all cases dependent upon its temperature; so that no coil can be assumed as a definite standard of ohmic resistance, unless the temperature at which it is to be used is specified in the standardizing, or unless the law expressing its change of resistance for a given change of temperature is accurately known. Even if the temperature is so specified to start with, we have no means of determining the temperature which the coil actually possesses at the moment of test, with any great accuracy, because this temperature is varying, and may be quite different in the interior of the coil from the indications of a
Thermometer placed in proximity outside.

It follows clearly, then, that any given coil, assumed as standard, may vary from that standard with different temperatures at which it is used; and this variation, though not wholly indeterminate, cannot be determined with any great degree of accuracy. Thus the so-called standards have, in themselves, a source of serious error.

Moreover, coils thus closely wound on small spools and grouped in the same box may possess widely different temperatures because of their structural inability to diffuse the heat generated in their interior; hence any temperature, recorded on a thermometer placed in the box, and assumed as the temperature...
of the coils, may not be the true temperature of any one of them. Evidently, therefore, the errors of the temperature measurement will quite probably be different for the different coils. It should, furthermore, be noted here, that the indication of the thermometer results not merely from the unequally combined effects of the various coils in circuit, whose temperature we need to know, but is, in part, due, also, to the temperatures of the other coils in the box which are temporarily short-circuited and idle, and with whose temperatures we are not directly concerned.

It follows, then, that we cannot make an accurate allowance for temperature error in one coil with any degree of confidence that it will be a true allowance for the next
coil on either side of it in the series. These temperature errors appear not only in the determination of the various resistances at the time of the test in which these are used, but they occur, also, though probably to a less degree, in the process of standardizing and adjusting the coils.

Strictly speaking, the coils are not exactly adjusted to equality with the standard, to start with, and their departure from equality is not exactly measurable by thermometric means; then, at the time of their use in any electric measurement, their departure from their initial approximate value is not exactly measurable.

It is apparent, then, that any resistance determination, involving the use of adjusted coils and dependent upon their values, is always a matter
of approximation more or less precise, but, in general, involving errors of considerable magnitude compared with those which remain in other lines of physical measurement conducted with equal care.

In brief, these difficulties in the accurate determination of temperature in resistance measurement are always vexatious, and often present a barrier to electrical testing of great precision.
To revert more specifically to existing types of resistance boxes, I may point out that in all the designs which I have examined, the spools, or bobbins, used, are of small diameter, so that the wire has to be wound layer on layer in a tight compact mass. It would seem to be a primary principle of good usage to design the coil so as to expose as large a surface as possible to facilitate the dissipation of the heat generated in the interior, but this consideration appears to be wholly overlooked.

Moreover, the bobbins are generally of heavy design, and mechanical attachment of each coil to the box is made directly through the medium of its respective bobbin; whereas, it is perfectly obvious that the bobbin
Should be of very light design, to offer a minimum impedance to the flow of the heat generated in the coil, and that the strength requisite for the mechanical support of the coils should, for the same reason, be obtained by a design requiring the use of the least possible quantity of material about the coil.

Then again, in nearly all types of boxes, the coils composing a single series of resistances are spaced much further than there seems to be any good reason for, in fact in one box I examined, the extremes of one series of coils were nearly three feet apart. It is evident that under such conditions a rise of temperature experienced by a coil at one end of
the box would not exert its whole effect in the coils at the other extremity, and any effort to get the true mean temperature of the coils must be appreciably in error.

The makers of this particular box had attempted to solve this difficulty by placing a solenoid of pure copper wire along the whole length of the interior of the box. This coil had a large surface exposed to the heat radiated from the bobbins, and had been adjusted carefully to the value of one hundred ohms at a definite temperature. The heat radiated from each bobbin of the series was supposed to exert its own proportionate influence on this long solenoid, and the effects from all the bobbins in circuit would thus be combined.
in raising the temperature of the one-hundred-ohm coil. The resistance of this coil was to be measured by a separate auxiliary bridge, or by a fall-of-potential method; and from its increment of resistance, the average temperature of the interior of the box, and hence of the coils, was to be computed. In general, such extreme refinement of method is justifiable only when it offers a decided gain in the precision with which results may be obtained. This particular box was designed for work of peculiarly precise nature, and the end may have justified these cumbersome means, but it appears doubtful that this method assures us of any marked advance in accuracy when used in ordinary laboratory practice, -- particularly when it is
remembered that the error is not really eliminated but transferred at least, in part, to the auxiliary bridge or the Clark cell.

A far more rational solution of the problem seems to be to keep all the coils of a series as near together as considerations of insulation resistance warrant, and to take direct thermometric readings at one or more points along the line.

I find a diversity of opinion as to the best method of jointing wires and terminals. Some makers prefer to use screw clamps without solder, for connexions; some use the simple solder joint; in some of the best designs, the ends of the two wires to be united are thrust into the ends of a short metal tube, of
diameter slightly greater than that of the wire, and this joint is then filled up with solder.

The use of screw connections without solder is open to the very obvious objection that the screw may work loose and so alter its resistance. Moreover, the paraffine almost invariably used on the bobbin, may insinuate itself into the joint and form an insulating film.

On the other hand, there is difficulty in making a soldered joint which will not vary its resistance slightly with age.

Of course, the use of an acid flux in soldering, is wholly out of the question, for the acid will remain continually at work at the joint and must eventually alter its conductivity, or may even eat
through the wire and break the continuity of the circuit. Electro-welding is perhaps the very best expedient to be thought of, but this is not as yet, generally available for this class of work; and we seem, therefore, forced to the use of a pure solder, applied without acid.

I have found it much easier to adjust a coil to equality with a standard when using good screw or mercury connexions, than when using solder. The reason is obvious. The heat of the solder, newly applied, not only alters the resistance of the circuit quite appreciably, but also sets up thermo-electric currents which may or may not neutralize each other. It is therefore necessary for each joint to cool to the uniform coil temperature before one may determine the resistance...
of the coil; but with screw or mercury
connections the local heating is almost
nil, and the thermo-electric effect far
less marked. At the same time,
in the adjustment of most resistance-
boxes the difficulty is of small weight,
because exact equality between the coils
and the standard is not aimed at,
but only a reasonable degree of ap-
proximation thereto;—then when the
temperature has become uniform, the
values of the coils are determined and
stated in a "Calibration Correction" for
the particular box under test; this
"correction" being itself subject to all the
errors enumerated in the first section
of this report.

The next point of note, in the
discussion of existing forms and de-
signs, is the immense bulk and
weight of the boxes in general use.

As stated above, the coils are spaced lavishly, as a rule; in fact in a great number of boxes, the coils themselves occupy scarcely a tenth of the whole interior of the box.

As a consequence of this liberal spacing, the terminal blocks require to be spaced out over a large slab of ebonite or other dielectric material, which, because of its large area and the weight of the coils which it supports, has to be given considerable thickness.

Lastly, the box, into which this heavy combination of coils and bobbins is fitted, is of massive design. It would seem, then, that through the whole process, the primary principles of good electrical and economic design are violated.
Instead of facilitating the flow of heat by the use of light, thin material, the dissipation and equalization are impeded at every possible point by thick walls, and heavy, clumsy design.

The lavish use of material in the bobbins, and in the heavy insulating slab, or cover, and the generous dimensions of the box are not warranted, in any sense, by the requirements of mechanical design,—if the accompanying design is correct—and, in fact, if the reasoning of these pages, with respect to radiation, dissipation and temperature, is true, these points of design are quite at variance with the necessities of precise ohmic determination through a range of temperature variation in the coils.
It will be seen more fully later, that the work of which the following is a report, proceeds along lines diametrically opposed to those outlined above as being illustrative of the ordinary practice. Thus, for instance, the coils are not separated widely from one another, but, instead, a special design is developed, by which they are brought into close proximity, so that the temperature change in one coil may be quickly taken up by, and distributed among, the other coils. The wires are not wound in compact air-tight layers; but, instead, they are spread open and left exposed individually to the air at every possible point. The coils are not imbedded in a thick mass of paraffine, but, being to a great degree free
from contact with each other or with anything else, may safely be
left without paraffine, except at certain points—(see Figs 5, 6, 16)—
and thus the diffusion of heat is still further facilitated.
The ebonite slab is neither thick nor of undue large area. It is re-
ceived wholly of the weight of the coils and bobbins, so that it may
be far lighter than in the present forms of boxes.—See Figs 15, 16.
The old type of heavy ebonite bobbin is wholly abandoned, and a type
of open frame is developed, one frame taking the place of a whole
group of bobbins. These frames secure the requisite mechanical strength
with the utmost simplicity of construction, and the use of the least
possible quantity of material.
Furthermore, the frame admits of strong and simple mechanical attachment to the removable lid of the box; it may be instantly removed from its position in case of injury to the coils it carries; it saves certainly three-fourths of the space required for the ordinary bobbins as they are generally mounted, and it gives perfect freedom to air currents among the strands of each individual coil and among the coils of the whole series. Figs. 10, 16.

From the saving of space just alluded to, it is evident that the box need no longer be large or heavy; on the contrary, it is made of greatly reduced dimensions, and a considerable saving of weight and material is thus effected.
Leaving, now, the discussion of faults in existing forms of resistance boxes, consider, next, the various lines along which the work to be herein described proceeds, and the several distinct purposes which it is deemed desirable to fulfill.

1" To improve the methods of winding a resistance coil so that its variation in temperature with the passage of a certain definite current shall be much less than at present.

2" To improve the method of winding such a coil so that although its temperature may vary, this variation will be exactly measurable, that is, so that the precise temperature of the coil may be determined by an ordinary thermometer.
3. Furthermore, to improve the arrangement of the various coils in a resistance-box, so that the variation in temperature of one coil, due to the passage through it of an electric current, shall be immediately felt by the other coils in the box. These will quickly assume, in consequence, a temperature which shall be far more nearly uniform throughout the box than is now possible, and hence capable of far greater accuracy of determination.

Several points of minor importance are reserved for their appropriate places in the body of the report.

Before proceeding further, it will be well to note, here, that
The heat generated in any bridge-coil of resistance $R$, by the passage of a current $C$, is proportional to $C^2R$; so that the temperature acquired by that coil increases rapidly with $C$. To minimize the heat error, therefore, we must keep the current as low as possible, since we depend on thermometric determination of the average temperature of the interior of the box; and if this is to be taken as even fairly representative of the coils in circuit, these must not vary much from those which, although equally effective on the thermometers, are, for the time, out of use. This feeble current quickly sets a limit to the sensitiveness of the bridge system; therefore, in order to keep the temperature errors small we are compelled to sacrifice
the degree of sensitiveness (to small changes in $R$) which we might otherwise attain in the determination of $R$, by the bridge.

The new method of winding and grouping coils is intended to facilitate the dissipation of the $C^2R$ heat, to such an extent, that it will become possible to use considerably greater battery-power in the bridge, and so correspondingly increase the sensitiveness of the arrangement.

The first of the three propositions enumerated above has, then, a double aspect. — We may say that for a given increment of temperature (corresponding to a certain assumed limiting value assigned to the temperature error), this new method should enable us, as just stated, to use a higher battery-power.
with a corresponding increase—
in the sensitiveness of the bridge—
and a consequent gain in the
accuracy of adjustment;—
or else, for a given limiting
value of current strength, we
should have the temperature varia-
tion of the coils confined to
more narrow limits and hence
the average temperature capable
of more exact determination.
Either of these results would
materially enhance the value
of all observations made with
these coils.

In brief, then, the logical
result of these improvements would
seem to be to place all electrical
testing and standardizing which
is dependent upon the accurate
determination of resistances, upon
as sure footing, by reducing, to a minimum, the temperature errors; for these errors are among the chief difficulties encountered in precise laboratory work; and aside wholly from the gain in respect of the electrical capabilities of the bridge, there would be a marked gain in convenience, portability and economy of construction.

I wish now to call attention, briefly, to certain other matters relating to existing designs of resistance box, in which improvement is certainly possible and desirable, no less than in respect of temperature determination. These matters, insofar as they are here discussed, are of two classes:
1st Points appertaining solely to questions of good mechanical design.
2nd Points appertaining to mistakes in "reading" the plugs of the box, or rather the sum of the resistances unplugged; and means for minimizing the chance for the occurrence of such mistakes.

Under the first heading, we find a source of considerable uncertainty and error existing in some boxes, not, however, those of first-class design. This is as follows:—The electrical connection between each coil and the corresponding block in the series of terminal or plug-contact pieces grouped on the insulating slab, is made through the medium of one or more of the screws used to hold the block in place.
upon the top-slab. These screws are subjected to excessive strains and lateral thrust, through the wedge action of the conical plugs; and they are quite often observed to work loose after a period of use. In this working loose, they become wholly unreliable, and worthless for electrical connections. In any event, whether they are loose or tight, there is still the ever-present menace which mere surface contact presents to the constancy of the resistance which embraces that contact. The presence of minute particles of grease or grit along the contact surfaces serves to effect a marked inconstancy of resistance; and, moreover, the surface resistance may vary quite appreciably with temperature changes.
The custom, in the better class of boxes, is to use heavy wires or tubes soldered firmly into the plug-contact blocks, and extending down through a perforation in the ebonite slab to receive the ends of the coils, to which they are also soldered. These connecting wires or tubes are, in a large number of boxes, used, also, to support the weight of the bobbins and coils, so that any mechanical shock the box may receive is transmitted, at once, to the soldered joint.

In my design, these connecting wires are entirely relieved of the support of the coils, which are held by a special wooden skeleton frame; and, moreover, they are attached to the plug-contact blocks, not below
the slab and hidden from sight, but up in plain view above the slab, where they may be inspected as often as desired; and, similarly, their attachment to the evils is made in such a position that, upon removing the bottom of the box, all these joints may be conveniently and quickly inspected. In short, an effort is made to differentiate the mechanical from the purely electrical structure of the box; to supply a sufficiently strong mechanical support for the electrical devices which shall take up, in itself, all mechanical stresses, and so relieve the electrical circuit and the insulating parts of the design, as far as possible, from mechanical strain.
Under the second heading, that of mistakes, I wish to note that mistakes are likely to occur even in a carefully guarded series of experimental data; that even the most skilled experimenter will occasionally make a blunder in observing or recording or in computing results.

A fact so well established, should certainly be borne in mind in designing any apparatus for physical determinations.

To lessen the chance for the occurrence of these mistakes, is a consideration certainly not second in importance to that of securing accuracy of adjustment in the apparatus.

While it is, in general, quite true that such mistakes will be
detected and thrown out, upon careful comparison and discussion of a series of results; yet, in such work as resistance measurements, where the observations sometimes have to be taken as rapidly as possible, and from the nature of the test do not readily admit of being checked, as in testing hot armature resistances and the like, - it is particularly essential that errors of observation should be guarded against by careful design of the instruments.

In a large number of instruments this principle appears to be recognized, and observations facilitated, and results freed from the chance of mistakes, by judicious design.

On the other hand, I know of no class of instruments in
which this consideration is more persistently overlooked than it is in resistance boxes.

The observer's sight is confused by a tangle of wires running to the various terminal screws on the ebonite slab; these wires generally overrun the plug-contact blocks and greatly increase one's chance of making mistakes in taking the "plug readings."

It may be urged that the experimenter is alone to blame for this, and that he should arrange the lead-wires more neatly along the sides of the box; but a sufficient answer is, that, in practical work, an observer is not likely to devote much time to arranging a neat set of outside connexions;—he will, as a rule, seize upon the first stray
lengths of wire he finds, and adapt these to the test in any way he can with the least labor and delay.

In the accompanying design, no lead wires approach the top slab of the resistance box—nothing intervenes between the observer's eye and the stamped resistance-number.

In fact, no binding-screws, or clamps are located upon this slab. The top of the box is devoted to the adjustment and observation of the resistances, and all connections to outside apparatus are made at one side on a separate ebonite slab, as will be more clearly shown later. Figs 16, 18, 19.
The second main line, along which there is a chance for making mistakes, in reading the plugs, is this:— in addition to the set of plug-sockets, at which the resistances are to be read, there is, on most boxes, a series of idle sockets to receive such plugs as are withdrawn from their contact sockets. The object of this is to afford a convenient and clean receptacle for the plugs which are, for the time being, out of use. This arrangement prevents mistakes. It is easy to confuse the two sets of sockets, and, consequently, read zero where a coil is really unplugged, or to read the resistance-number stamped next some open idle-socket, when the corresponding contact-plug is really short-circuiting.
There is no valid excuse for such blunders, but I have known them to occur repeatedly in work that was supposed to be carefully done, and they will occur as long as human agency is fallible.

In the accompanying design, no idle sockets are provided on the bridge top; but, instead, a series of these sockets is secured to the inside of the outer cover of the box. The cover, though generally kept closed upon the box, is, during a test, laid conveniently at one side to receive the plugs; and as it is designed to give the plugs, when out of use, the protection from contact with dirty or greasy surfaces which it is so requisite for them to have, the utility of the scheme is apparent.
It is useless to take care to keep the insulating surfaces clean and bright, or to cleanse the sockets, if the plugs themselves are to be laid on a dirty table, or held in the operator's hand, which is certain to have more or less oily exudation.

Two photographs of the new design are appended. One shows the arrangement of the top slab, the box being placed on its side; the other shows the group of terminal- or binding-posts at the side of the box (connected to the corresponding points of the line of contact blocks on top of the box. Both show also, the rows of idle sockets in the cover.

A glance at these photographs, or at the model itself, will show how much the design does to facilitate readings, and to keep the idle plugs in a condition consistent with careful coil-calibration.
Another point comes up, in connection with the subject of plug-contacts. The conical plugs are usually fitted with large ebonite handles, which afford considerable leverage for wedging the plugs into the sockets.

I have convinced myself, by careful experiments, that there is no appreciable gain in thus forcing the plugs into the sockets. A clean well-ground brass plug was set lightly in its socket, and given a slight downward spiral motion, merely enough to prevent its moving when touched with the finger; its resistance was then determined. The same plug was now forced into its socket as violently as the apparatus would bear, and its resistance again determined. The difference was hardly perceptible between these two
measurements;—its order of magnitude in ohms was, at most, in the fourth decimal place.

It is evident, then, that no advantage accrues from forcing the plugs into place;—on the contrary, forcing one only serves to loosen the next in series, to strain the contact-blocks and throw the accurately fitted sockets badly out of alignment.

Moreover, if the plug is at all gritty, the forcing action will cut it badly, as well as the surface of the socket. These effects are so well marked, that continual violence to the contact surfaces will eventually make the best of resistance-boxes totally unfit for precise work.

In the new design, I have sought to lessen this danger, by making the plug of larger radius—relatively
to the handle; that is, the handle does not offer much leverage for forcing the plug into place, so that it is practically impossible to insert the plugs with the degree of violence that inexperienced or nervous experimenters generally use on the ordinary lozenge-shaped handle.

Work, in accordance with the three fundamental propositions enumerated on page 24, naturally resolves itself into the following order:

1° To select a suitable metal or alloy; that is, one whose specific resistance is high, and whose temperature coefficient is the lowest to be found and accurately known.

2° To experimentally determine this coefficient in the case of a wire drawn from the selected metal or
alloy over an extended range of temperatures.

3° To test this wire, both before and after subjecting it to an excessively high temperature, such as might be caused by the accidental passage through it of a current in excess of its rated carrying capacity, to determine to what extent, if at all, its specific resistance and temperature coefficient are altered by this process.

4° To wind this wire into close airtight coils, designed in accordance with prevailing methods; also, into open, ventilated coils designed as indicated later on; and then to compare the temperature variations and resistance variations of these two types due to the passage through them of the
same uniform current.

5. To discuss these experimental data, to discover to what degree the new method is successful in accomplishing the purposes stated in the three fundamental propositions on page 24.

6. If the success of these tests warrants it, to proceed to completely design and furnish working drawings for a box built in accordance with these new ideas of winding and grouping coils.

7. To construct a full-sized model of the box thus designed, embodying all the improvements and changes herein suggested, and equip it with a specimen of the ventilated coils.
First, then, as to the selection of a suitable alloy—since there is no single metal possessing the requisite characteristics.

What are these necessary characteristics?
I. The alloy must have a low temperature coefficient, and this must be determinable and fitted to a simple mathematical expression.
II. It will preferably have a high specific resistance, so that excessive lengths of wire need not be used for securing the desired resistances.
III. It must not be brittle.
IV. It must especially stand bending around the shank of the open-work bobbin without danger of fracture, or material alteration of its resistance at these curves.
V. Its specific resistance and temperature coefficient must be
proved to be constant, over a period
of years of use.
V Its resistance should not be
permanently altered by a temporary
but excessive rise of temperature.
VI It must be commercially
available.
VII Its thermo-electric value should
be determined, in conjunction with
brass or any other metal to be
used for the plug-contact blocks,
and the thermal electro-motive force
of the couple thus formed should
be low.
VIII Its composition should be quite
uniform so that the specific resistances
of different samples of it may be
alike. Uniformity is, probably, of
still greater importance in connection
with constancy of the temperature-
coefficient, because each individual
coil may be adjusted to the desired value, by direct bridge measurement, but the temperature coefficient is generally taken from the results of tests on samples of the wire, and assumed to apply to the whole quantity manufactured. This assumption can be true only when the composition is constant within very narrow limits indeed, and the process of manufacture of successive quantities carried out along the same uniform lines.

Other essential characteristics are sufficiently obvious.

Many experimenters are still actively at work, attempting to produce an alloy composed of a metal possessing a positive temperature coefficient combined with a metal of negative coefficient; the combination
to be in such proportions that the two shall just offset each other; -
the result being an alloy whose
temperature coefficient is, at least
for ordinary ranges of temperature,
entirely negligible. Unfortunately,
alloys do not possess, in general,
the precise qualities which our knowledge
of their constituents would lead us to
expect, but exhibit characteristics
surprisingly different from those of
any one of the metals which enter into
their composition. This phenomenon
complicates matters so much that, so
far, the search for an alloy qreally
negligible coefficient has not yielded
practical results. At least, it is
safe to say that such an alloy is
not, as yet, commercially available.
A rise of temperature in a
coil affects, - or may affect - the results
of measurements made with that
coil in the three following ways:

-a- The rise in temperature causes a
temporary alteration in the true
resistance of the wire.

-b- The rise, if excessive, may cause
molecular changes in the wire which
will bring about permanent change in
its resistance.

-c- The heating sets up thermal
electromotive force which interferes
with that of the bridge battery
and distorts the result of the test
which is in progress.

Granting, therefore, that an
alloy may be obtained whose tem-
perature coefficient is wholly eliminated,
we see that it is still necessary to
avoid temperature differences on account
of -c-, and -b- remains still in force,
unless proved otherwise for the
particular alloy. Therefore, the efficient ventilation of the coils remains a matter of no small importance, whatever alloy is used; except in the improbable event of an alloy of negligible temperature coefficient being found, whose thermal electromotive force, in conjunction with the other metals used in the circuit, would be zero.

The temperature error is unquestionably, I think, as a rule, of greater magnitude than that from the thermal e.m.f., because this latter can be partially eliminated by a method of current reversals; still the elimination is not always complete, and, in extreme cases, the error from this source is very considerable.
Copper and iron were used for the earlier resistance coils. Iron wire and sheets are still used where the object of the resistance is merely to dissipate electric energy. Copper is not much used for it is far more costly than iron and not nearly as useful for the purpose.

German Silver has long been and still is used in the majority of resistance-boxes, but it is, at best, a makeshift to tide over the interval till something better is developed, for its specific resistance is not sufficiently high, nor its temperature-coefficient sufficiently low, to really meet the needs of the case.

Platinoid has lately come into extensive use; its specific resistance is materially higher than
that of German silver and its temperature coefficient is considerably less. It is not certain that its coefficient can be made to be uniform among a variety of samples of the alloy, nor that it is constant over a period of years. Moreover, its specific resistance is not well defined. In testing a great quantity of wire (of many different gauges) of this alloy, I have found marked differences in the specific resistances of lengths taken from the same gauge, and even from the same spool. I have not found it easy to make a good solder joint with this alloy. It is, as I have intimated, largely used, at least in Europe, by makers of resistance boxes.
One of the most recent additions
to the list of alloys is Manganine.
Its specific resistance has been variously
stated. It is probably somewhat higher
than 30% German Silver, perhaps even
quadruple that. Its temperature coefficient
is exceedingly low, but not, as yet,
determinable in advance. It depends
for this coefficient, upon the degree of
temper which it possesses, a slight change
in the drawing suffices to alter its
coefficient quite appreciably. Still, it is:
at all times, lower than German Silver.
I determined to use this alloy, and
knowing that some time would be
necessary for getting it made and
silk-wound, I wrote to London for it
early in December. A satisfactory
reply was promptly received, but, after
waiting many weeks for the shipment, I
inquired as to the delay and found,
that, through a blunder in the office of the London firm, the order had not been filled and could not be filled in time for my experiments. I hastily made inquiries among prominent American firms and found that, although it could be procured in this country in large gauge numbers, the makers were not prepared to supply it in small gauge numbers suitable for bridge coils.

I found, however, that the Weston Company have produced an alloy of composition nearly identical with manganese, and which possesses the following characteristics, according to the statement of the company ......

"With 30% of manganese, in a manganese copper alloy, we have ...... a coefficient of -0.00007 and a specific resistance of 5.3 microhms" ... etc. In another place they say that the coefficient of an alloy
made by them has been found to be as low as +.00001. Both of these figures are negligible for bridge work of a precision of one-tenth percent, which is really the maximum precision aimed at in nearly all classes of tests made with the Wheatstone bridge.

This alloy also possesses a remarkably low thermal e.m.f. in conjunction with brass, so that it would seem to be an ideal composition for use in bridge coils, particularly as wound on the new open frames where, because of the good ventilation obtained, the heating and the consequent thermal e.m.f. effect would probably be altogether negligible.

So far, the makers have not supplied me with this new alloy. Therefore, I have concluded to use German silver for the experimental work.
of this work.

No doubt the new alloy will soon be placed on the market, and then, if the experimental data given out by the company are verified by independent tests, the alloy will unquestionably come rapidly into use.

The figures quoted above show that, in so far as the errors due to heating effects are concerned, the new alloy may be used in gauges much smaller than those now used in Wheatstone bridges, and still the temperature errors will be negligible. This means that the size of the bridge may be still further reduced; though in my design the usual gauges are followed.

Being unable to secure the necessary quantity of the new alloy from the makers, in fact unable to get any of it whatever, as stated, I have chosen German Silver for the experiments as being best illustrative of recent practice.
In the accompanying model, space is provided for coils of German Silver or manganine wire or the new Weston alloy of the following lengths and gauge numbers.

### Ratio Coils

<table>
<thead>
<tr>
<th>Value (ohms)</th>
<th>Length (ft)</th>
<th>3%</th>
<th>B &amp; S Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>95</td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>1000</td>
<td>220</td>
<td></td>
<td>32</td>
</tr>
<tr>
<td>10,000</td>
<td>350</td>
<td></td>
<td>40</td>
</tr>
</tbody>
</table>

### Bridge Coils

<table>
<thead>
<tr>
<th>Value (ohms)</th>
<th>Length (ft)</th>
<th>Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>1/8</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>1/8</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>1/8</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>1/8</td>
</tr>
<tr>
<td>10</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>45-</td>
<td>22</td>
</tr>
<tr>
<td>30</td>
<td>42</td>
<td>24</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value (ohms)</th>
<th>Length (ft)</th>
<th>Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>95</td>
<td>26</td>
</tr>
<tr>
<td>200</td>
<td>110</td>
<td>28</td>
</tr>
<tr>
<td>300</td>
<td>106</td>
<td>30</td>
</tr>
<tr>
<td>400</td>
<td>145-</td>
<td>30</td>
</tr>
<tr>
<td>1000</td>
<td>220</td>
<td>32</td>
</tr>
<tr>
<td>2000</td>
<td>220</td>
<td>35</td>
</tr>
<tr>
<td>3000</td>
<td>200</td>
<td>37</td>
</tr>
<tr>
<td>4000</td>
<td>220</td>
<td>38</td>
</tr>
</tbody>
</table>
The above gauge numbers are lower than those used in the majority of boxes and so, taking gauge numbers from boxes accepted as standard, we might use considerably finer wire - i.e. higher gauge numbers as follows:

<table>
<thead>
<tr>
<th>Value</th>
<th>Length : G. D.</th>
<th>B &amp; S. Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^w</td>
<td>21 feet</td>
<td>#22</td>
</tr>
<tr>
<td>100</td>
<td>55</td>
<td>28</td>
</tr>
<tr>
<td>1000</td>
<td>110</td>
<td>36</td>
</tr>
<tr>
<td>10000</td>
<td>350</td>
<td>40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value</th>
<th>Length</th>
<th>Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>10km</td>
<td>6 feet</td>
<td>#18</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>24</td>
</tr>
<tr>
<td>30</td>
<td>33</td>
<td>26</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>26</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Value</th>
<th>Length</th>
<th>Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>100^w</td>
<td>58</td>
<td>#28</td>
</tr>
<tr>
<td>200</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>300</td>
<td>70</td>
<td>32</td>
</tr>
<tr>
<td>400</td>
<td>100</td>
<td>32</td>
</tr>
<tr>
<td>1000</td>
<td>110</td>
<td>38</td>
</tr>
<tr>
<td>2000</td>
<td>140</td>
<td>37</td>
</tr>
<tr>
<td>3000</td>
<td>180</td>
<td>38</td>
</tr>
<tr>
<td>4000</td>
<td>140</td>
<td>40</td>
</tr>
</tbody>
</table>
By using these finer wires not only is the cost of the box considerably reduced, but the outside dimensions of the box can be reduced by one inch all around, or else, with the present dimensions, the coils can be spread out much better, thus more closely fulfilling the conditions which the bridge was designed to meet.

The tables give the lengths of 35% German silver wire needed for each coil, a small margin being left for adjustment and possible variation in specific resistances. The lengths of manganine or Weston alloy would be slightly less, but no exact tables of specific resistances of these alloys are, as yet, available.

Again, as I have already intimated, we might use still finer wires, because of the exceptional facilities for ventilation in the new design.
Next, as to the choice of an insulating material of which to make the skeleton bobbins.

Wood is only suitable for the roughest, cheapest work. It is an indifferent insulator, but this might be corrected by thorough preparation with paraffine, at least sufficiently for use as bobbins. At present, however, a further difficulty: Coils, once wound and adjusted, must not be altered as to shape, in the least degree, for any such alteration sets up a new set of strains along the length of wire, brings the adjacent layers of the coil into new relative positions and may quite upset the adjustment of the resistance, particularly if the wire is poorly insulated, and in none of the wire ordinarily supplied for resistance coils.
is the insulation wholly trustworthy. Wood, in warping, undergoes all sorts of changes of form; and, however carefully seasoned it is, it cannot be trusted to retain its exact shape under the stress of the tightly wound coil.

From a number of available insulators, I selected Hard Fibre for my first open-work frames or bobbins.

Specimens of this material which I have had in my possession for two years, do not show any appreciable alteration of shape; they retain the degree of surface finish which they originally had, after two years of exposure to damp and dry air, in a variety of climates. The specific resistance of this substance, when dry, is high enough to warrant its use
for the open frames; it is cheap and easily turned, sawed, or cut to the required shape; it is tough and strong.

On the other hand, word has just reached me from a reliable source that some electricity meters, which had been insulated with washers of this material, broke down completely in insulation resistance under moderate voltage after exposure to moist air.

It would seem, therefore, that some samples of this material are decidedly hygroscopic. If this be so, it is utterly worthless for bridge bobbins.

On the strength of the above information, in the absence of more evidence, except my own, I have abandoned Hard Fibre and now suggest Ebonite as the most suitable
material, in conformity with the usual practice.

I find ebonite to undergo very marked deterioration (at least as to surface finish, upon which we chiefly depend for high insulation) upon long exposure to air which contained traces of acid, but it is certainly not hygroscopic.

I have observed that of two instruments used in the same room and therefore subjected to the same atmospheric conditions, that one which was protected from daylight, experienced far less deterioration of the polished ebonite top than the other, which was not so protected, though the acid fumes were always present in the air of the room through to a varying but never excessive degree.
Of course, in a resistance box, the ebonite of the bobbins is always protected from sunlight and the top slab may readily be kept covered except when in use; so that there appears to be little danger from surface deterioration.

With this material in hand, the problem which next arises is as follows:

To design a frame upon which to wind the coils, and which shall:

- a - permit the coils to be in close proximity;

- b - hold the layers of each coil open as much as possible, so that air may circulate in and out through the layers of the coil;

- c - permit perfect freedom to the air currents among the whole series of coils throughout the box.
-d- be mechanically strong, and absolutely rigid, and yet light and thin, simple, and easily and cheaply made.

After carefully considering various possible forms, I have developed the design shown in Plates II and V. This may be made of exceedingly light, thin material, and will possess great strength to resist the compressive stress of the coils; it has surprising rigidity against end-thrusts and twists, and is perfectly simple in construction. It also admits of easy and secure attachment to the supporting frame of the box. These latter points, also the great saving in bulk accomplished by the design were noted in an earlier page. Its cost is but a small fraction of that of the ebocite bobbins usually employed.
Another, and still more important result accomplished was also noted briefly above on page 22.

It has been repeatedly referred to as the first thing to be aimed at in designing a resistance box, and it forms the chief feature of the new design, as distinguished from the older types; namely: the wire touches nothing whatever except at the necessary points of support, so that air currents have perfect freedom among the turns of each coil and among all the different coils of the box.

Though the coils thus touch only the supporting bars, they are really as close to each other as is consistent with efficient ventilation and security from insulation leakage; so that the flow of heat and consequently the equalization
of temperature among the coils, is facilitated to the utmost possible degree, in conformity to the principles which have been emphasized above.

In connection with the design of the frame it may be well here to note a matter in connection with the arrangement of the coils comprising the ratio arms of the bridge. The amount of heating effect which occurs in these coils is, of course, proportional (in each coil) to \( C^2R \), as shown on page 26. The temperature of the coil will depend upon \( C^2R \), upon the specific heats of the mass of the coil and bobbin, and, upon the degree of ventilation provided for the coil. This rise of temperature in the ratio coils will be negligible, within ordinary limits of variation, under the following set of conditions.
-a- The two sets of cells must have the same temperature coefficient.
-b- They must start at the same temperature and attain the same final temperature under the C*R effect.
-c- The thermal Electromotive Forces in these two opposing arms must just offset each other.

Condition -a- is fulfilled quite closely in standard alloys; and the new design tends still further to reduce the error, here by keeping the total temperature change within more narrow limits.

Condition -c- is troublesome, and we must reduce it, likewise, by keeping the whole variation within bounds.

After these two conditions are fulfilled, Condition -b- remains.

In most cases this condition of equal temperatures is met only in the
noughest degree of approximation. Suppose the two coils in use to be of 10000 and 10 ohms respectively, and the same current to pass through both. The first coil will have one hundred times the heating effect of the second; but the masses of the coils and bobbins are sensibly equal in the two, and their abilities to diffuse the heat, not widely different. Or, suppose another arrangement of battery so that these same coils receive current in the inverse ratio of their resistances. Then the ten-ohm coil gets one hundred times the heating effect of the thousand-ohm coil; the same great difference, only manifested in the reverse direction.

Under such circumstances, there must result a difference of temperature between the two ratio arms, not
at all easy to measure by the ordinary thermometer inserted, at random, into the box, but quite sufficient to have an appreciable bearing on the accuracy of the results obtained with these coils. The solution of the difficulty appears to be, to wind, in juxtaposition, those coils of the opposite arms which are most likely to be used together, and thus maintain the necessary conditions of equal initial and final temperatures much more closely than at present. Thus, in the case assumed above, the coil which experienced one hundred times the heating effect of the other, would immediately impart some of this excess to the cooler one and to the others of each set next it, and thus the excess would tend to be its own corrective.
With respect to the model submitted with this report, I wish to state that there are several particulars in which it differs from the design herein suggested, in minor details only, the main features of the design being rigidly adhered to.

It is interesting to note the result of one of these deviations from the design. It was stated above, that it seemed desirable to make the soldered joints between the brass blocks and the wire connections rise above the surface of the ebonite where the condition of the joints could occasionally be inspected. The general appearance of the bridge box would, of course, be somewhat injured, but the plan seemed, nevertheless, worth following. However, in the model, because of the greater labor and cost in having these joints neatly,
made on top of the box, I decided to follow the old plan of hidden joints made from the inside of the box. The result is that, though this work was done by a skilled mechanic, several of the soldered joints worked loose, in the process of adjusting the shape of the connecting wires to fit the contour of the bobbin, their resistance became altogether an unknown quantity, and if not discovered, as, by chance, they were, they would have upset the calibration of any coils that might be placed in the box and connected to them. This experience, quite unimportant in itself, proves quite conclusively to me that any soldered connections in a resistance box, which are hidden from sight, are a menace to the accuracy of results obtained with that box, and should not be tolerated if they can possibly be avoided.
The bottom of the model box is easily removable, giving full view of all the coil junctions; and each side of the box is separately removable, so that one may have clear view of the frame and bobbins all around, without touching or disturbing them in any way. Had my original determination to make the block connexions on top and in plain sight been adhered to, the model would, in this particular, agree with the design exactly.

A second point, in which the model is different, is as follows. It was stated on page 71, that the ratio coils should be wound with corresponding coils of the two arms in juxtaposition. The practical difficulty which arose was to determine what were really corresponding coils; which of the several pairs were most likely to be used together. Any expedient which, like this scheme, on page 71, is to be
resorted to for the purpose of eliminating a certain error and implicitly trusted to correct that error, and then in practice is only partly carried out, is really worse than the original error, to which, as a calculable quantity, an approximate correction might have been applied in the first place.

In view of this, it is deemed better to wind the ratio coils all in a line and packed closely together, but yet thoroughly ventilated, like the other bridge coils. So the model is built with ratio bobbins just like the other bobbins supplied for the bridge coils. What is, according to the new design shown in figures 4 and 5.

In case a bridge were to be built for purposes of a special line of tests, requiring ratios of 1000 to 10 for instance, and no other ratios, these two coils should certainly be wound together to secure all the benefits of temperature.
equalization.

For such winding, the bobbins would be of the same general type as those used in the accompanying model, but the ovals of ebonite would be spaced much further apart, to permit the coils wound in juxtaposition to spread well out laterally for better ventilation, and this wider spacing would necessitate considerably heavier rods for resisting the bending effect of the winding.

The wooden supporting legs, for the three rows of bobbins, have been given greater strength than the design indicates, because it was found that the wood used, mahogany, was rather brittle. Legs made of well seasoned pine could be cut to even smaller size than those shown in the design.

A complete set of plugs is not supplied with the bridge. The two plugs
supplied suffice for the purposes of the model, and the expense of a full set seemed unwarrantable. The plugs require skilled labor, and form one of the chief items of cost.

Two small sliding doors are cut in the lower left front and the upper right back wall of the model. The hot air, thrown off from the coils will naturally rise, flow out through the top door and draw in, after it, a stream of cool air through the lower door. These doors would be thrown open whenever heavy currents were being used in the coils, but, for ordinary bridge work, might be closed, as the admittance of dust to the coils and ebonite rods is ordinarily to be avoided.

I find unexpected justification for the introduction of these doors into the design, in statements made by various
members of the laboratory staff here. It appears that the Wheatstone bridges in the laboratories of the Institute are unfit for use on Monday morning, because the building, ordinarily warm, is left unheated during Sunday; consequently, the bridges slowly acquire this low temperature until, by Monday morning, they are thoroughly cooled. But now, the building is heated quickly, and the bridge interior lags, in its temperature, 8 or 10 degrees Centigrade behind the room, showing it wholly out of the range of precise work. By afternoon, this effect has disappeared. The sliding doors may be counted upon to do away with this annoyance.
Not wishing to delay my experimental work until the completion of the model, I constructed a rough resistance box, embodying the principles of the model, with which the actual experimenting has been done. This box consists of a portion planned to secure the conditions of ventilation as found in the model, and another entirely distinct portion planned to duplicate the conditions which exist in an ordinary bridge. To these ends, the box was made of thick wood with a tight-fitting lid (also of wood). A partition of 1\(\frac{1}{2}\) inch pine divided the box into two compartments. The larger of these compartments was ventilated by boring a number of one-inch holes through the outer walls of the box. The smaller compartment was left practically airtight. In the ventilated compartment, I placed one of the skeleton frames of
ebonite, see fig. 6; and on this frame I wound a German silver coil of approximately 200 ohms resistance, spreading the turns of wire out well laterally, to obtain the best possible ventilation. By the side of this coil, and separated from it by only one of the ebonite ovals, I wound a two hundred ohm coil of copper wire. This wire was finer than the German silver wire, and a greater length was used, thus bringing its resistance to nearly the same value as the other, with a mass of metal not very different from the mass of German silver. This copper coil was intended to be used as a temperature coil; and copper was used because, for a given temperature rise, its variation would be much greater than one wound of German silver, and the temperature determinations, therefore, could be made
with greater precision.

In the air-tight compartment was placed a heavy spool much like the ones used in the ordinary resistance-box except that, as it was only for temporary use, it was made of wood, boiled in paraffine. On this spool was wound, in tight close-lying layers, a coil of German silver wire, exactly like that used on the open frame in the other compartment, and measuring 200 ohms. The terminals of the copper coil were brought up to ordinary binding posts on the box lid. As heavy currents were to be used in the German silver coils, unusual precautions were taken to avoid thermo-electric effects at all terminals. The ends of the coils were firmly soldered to heavy German silver lead wires, and these were brought up
Through the top of the box and fastened to terminal plates with solder.

These terminal plates were of peculiar design, and were planned to cut down the thermal effect of the junctions to a negligible amount. Each plate was of German silver two inches square and one eighth of an inch thick. Two metal legs were fastened to it, and these were fitted with screw threads and nuts. These legs were thrust through holes bored in the box-lid, and fastened from below. In order to utilize both surfaces of the German silver for ventilation, and to decrease the wood surface along which leakage might occur, the legs were fitted with small washers, before being placed on the box-lid. These washers held the plates one sixteenth of an inch up from the wood. Molten solder was smeared
all over the wires where they joined the plates. The wood-work was thoroughly treated with shellac.
There was no perceptible leakage from block to block, with the battery power used. The mass of metal was amply sufficient to take care of the thermal effect by preventing local heating.

Three of these blocks were used; one at the junction of the two German silver coils, and one at each outer terminal; to them, the necessary bridge connexions were brought.

The first method of testing was, to connect the two ends as the ratio arms of a bridge, and to complete the bridge, by means of an ordinary resistance box. The ratio was very carefully determined, cold; and then the coils were heated, by the passage of a current, for a certain time, and their ratio again
determined while they were hot.

The difference between the hot and cold ratios was the quantity sought.

In the following record of observations, these ratios show that the unventilated coil has grown not much faster than the ventilated coil. In fact, the difference between them amounted to more than 0.001 per cent of the total resistance of the coils. The significance of these results in bridge work, of a precision of 0.01 per cent, is obvious. They mean simply that the fourth significant place of figures, in the results obtained in bridge work, usually uncertain to one or two units, is made more reliable by the amount of at least one unit.

But these results, interesting in themselves, did not wholly cover the ground mapped out. They were merely ratios, and it was necessary to find whether
the ventilated coil, alone, was undergoing any great temperature changes. So, the method of work was changed. The exact resistances of the ventilated and unventilated coils were determined with all usual thermometric corrections. Then a current was passed through them, for a predetermined time, and their resistances again determined, as closely and as quickly as possible. Thus, I had, not merely the hot and cold ratios, but the exact hot and cold resistance of each coil.

These results were more conclusive. For instance, the passage of a current from nine Delanché cells through the ventilated coil continuously for ten minutes, failed to produce any measurable heating effect.

With the prevailing type of bridge, two cells are commonly used as a number
to be exceeded, only in exceptional cases.

If the sensitiveness of the bridge increases with the number of cells, in direct ratio, and the new coils will take care of the current from ten cells, it would seem that the results of bridge testing are placed, at once, on a much higher basis; the precision being quadrupled—for any given set of coils and galvanometer—unless the plug contacts and other sources of error are such as to prevent. But plug-contact and other errors may easily be cut down. The uncertain temperature variation has long been the chief obstacle to great precision in bridge work.

I will quote the data of the tests made with the ratio connections, and the others made with the individual determinations of each coil, indicating what degree of reliance the various results are worthy of.
The first test made by the first method (of observing merely the "hot" and "cold" ratios) gave the following results.

Ratio of coils - unventilated to ventilated coil -

before heating = 10014 : 10019.

after heating = 10014 : 10008...

change of ratio in favor of the
ventilated coil = 0.1%

The time during which the current was sent through the coils was 30 minutes. No. of cell = 16.

A second check test was now taken, using different ratio values, and repeating the calibrations for the bridge coils and their temperature. An interval of half-an-hour between runs was always allowed (and after the long run much more was allowed) to restore the two experimental coils approximately to their original temperature, so as to keep the results more uniform for checking. This second run indicated, also, 0.1% in favor of the ventilated coil.
The next run,—the one referred to as the long run,—was as follows.

Ratio of unventilated to ventilated coil before run = 99.95
— 5 hour run —

after run = 10.05

This shows a decided advantage for the ventilated coil. The difference of ratios is now 0.55% of the value of the original ratio.

In other words, if the unventilated coil had risen 13° Centigrade, while the ventilated coil remained constant, we would have expected a change of 0.05% in their ratio, from the known coefficient of German Silver; but careful thermometric readings showed that there had been no total rise, of any great magnitude, in the neighborhood of the ventilated coil; certainly less than one degree. The conclusion was, then, positive,—the ventilated coil had completely dissipated its heat to the air; and the unventilated coil had stored up all its $C^2R$ effect in itself.
These tests, having for their result, the difference in the ratio of two coils, are necessarily, of rather poor precision. This difference was of the first decimal place (in ohms), and the whole quantities measured were in the hundreds of ohms. As the bridge was suitable for work of only four significant places of figures, accurately determinable, with the fifth place uncertain to 2 or 3 units, no further refinement of the method was possible.

The values of the experimental coils were thus known to four places definitely, their variations of ratios to each other were of the first decimal place (in ohms) which represented the fourth significant place, the coils being 200° each. So then, only one place of significant figures could be depended upon, in the ratio variations, there being errors of 4 to 5 units in the fifth place, representing possible average deviations in the successive determinations of ratio changes, as high as 25 or
30%. However, the utility of the scheme for ventilating the coils was abundantly indicated, and I now changed the method of work to get, not merely ratios, but the individual values of each coil's resistance when hot, and again, when cold. These data would give an indication of the exact distribution of the total $C^2R$ effect between the ventilated and the unventilated coils. The coils were, therefore, in the next series of tests, measured separately by the Wheatstone bridge, before and after each run, with all corrections applied. Of course, the difficulty was that, while balancing the bridge for one coil while hot, after the run, the other coil would cool, so that the two determinations would not be under precisely identical conditions. However, I arranged the apparatus to get both results as quickly as possible, and always measured the ventilated coil first, thus giving the old type unventilated coil the benefit of the delay.
The first test by this second method gives the following results.

In each case, the necessary corrections and reductions to standard temperatures have been observed.

1) Initial value of unventilated coil = 199.5 \(^\text{\textdegree}\)
2) " " " ventilated " = 199.6 \(^\text{\textdegree}\)

Current turned on as before for 15 minutes

3) Final value of unventilated coil = 199.81 \(^\text{\textdegree}\)
4) " " " ventilated " = 199.60 \(^\text{\textdegree}\)

That is to say, the unventilated coil has risen in value 0.3 \(^\text{\textdegree}\) corresponding to 0.15\%

While the ventilated coil does not indicate any rise at all; in fact, according to the recorded data, the final value was one part in ten thousand less than the initial value.

But that is well within the limits of error in these bridge observations.
The rise of 0.15% found in (3) indicates a rise of temperature in the body of the coil (over and above that occurring meanwhile in the room—corrected out) of about 4° Cent. While the temperature of the ventilated coil has risen so little that its effect on the resistance of that coil has not begun to be noticeable. These results confirm those obtained in the first series by the ratio method.

Both methods are open to the objection that the differences of resistance observed are so small in comparison with the total resistance in circuit that any great precision in their determination is out of the question.

For future work along this same line of experiments it would be desirable to use a galvanometer of sufficient sensitiveness and a bridge of sufficient nicety of adjustment to give five places of significant figures, with considerable precision.
Then, being able to secure results with very small deviations, one should pass currents through experimental bridge coils, some wound without ventilation, some with the degree of ventilation obtained by the device I have employed in the accompanying design and in the experiments quoted, and still others ventilated by a further extension of the ventilating arrangement. Then, data should be collected for the rise of resistance through temperature due to a certain definite current; the tests embracing a series of runs from one minute, or less, to an hour. Similar data should be taken for slightly heavier current rates, and so on up to the full carrying capacity of the coils. Thermal effects would be troublesome, but, by using the massive connecting blocks I employed in the tests, these could be cut down. In this way one could plot a series of curves embracing all current strengths.
suitable for bridge coils, and all the time intervals—no. of minutes for which current was passed through the coils—which it would be reasonable to include. These curves would be plotted for specimen coils, of the ordinary spool pattern, for the new open-frame coils, and for any other patterns which might be designed.

A discussion of these curves would indicate to what precise extent ventilation could be made practically operative for eliminating bridge errors.

Such tests should include numerous alloys, and would settle, for the first time, the vexed question of maximum current-carrying capacity of bridge coils. Such a series of tests would require exceptionally good conditions for working, since great precision would be necessary in the measurement of very small quantities.
This thesis was primarily intended merely to present an improved design for a resistance box embodying the principle of coil-ventilation in an entirely original manner, and to include tests directed simply toward proving and supporting the claim of improvement in ventilation. But had suitable alloys been available—such as the new Weston alloy which I hoped to employ in my tests, but was unable to obtain—I would have been inclined to carry these experiments out of the scope of this report, and take up the general discussion of current-carrying capacities, but such work is of immense scope, and was quite out of the question.

In conclusion, I quote the final seen made with heavy current, for a period of 45 minutes, by the second method-page 84. It shows how thoroughly the new design brings the temperature error, from reasonable.
battery power, under control.

Ten cells of dynamo battery were used in series with 400 ohms.
The first column* gives time intervals. Readings were taken after the current had been on 5 minutes, the connections were remade as quickly as possible, and the current continued for another 5 minutes, and so on until no further increase in the ventilated coil was observable.

The second column* gives values of the temperature coil corrected for bridge temperature and calibration errors as determined at the 5-minute intervals.

The third column (vertical) gives the % rise experienced by this coil, simply written from the preceding column.

The fourth column gives the successive values of the experimental coil wound according

*vertical
to the design in Figs. 4 & 5, (being the same as used through all the tests).
The fifth column gives % rise of the resistance of the coil.

Temperature of room constant at 21°C.
Temperature of bridge coils constant and therefore negligible in the determination
- of the successive increments of column 4.

<table>
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<tr>
<td>0</td>
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<td>—</td>
<td>200.7</td>
<td>—</td>
</tr>
<tr>
<td>5</td>
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<td>0.20</td>
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<td>0.35</td>
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<tr>
<td>10</td>
<td>242.26</td>
<td>0.40</td>
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<td>1.000</td>
</tr>
<tr>
<td>15</td>
<td>242.46</td>
<td>0.10</td>
<td>Same</td>
<td>0.000</td>
</tr>
<tr>
<td>45</td>
<td>242.56</td>
<td>0.04</td>
<td>Same</td>
<td>0.000</td>
</tr>
</tbody>
</table>

The rise in resistance of the temperature coil lags behind the heating effect in the adjacent current-carrying coil. The copper temperature coil carried no current, of course.
Its change of resistance was due solely to the heat received from the current-carrying ventilated coil.

The ventilated coil rose, in five minutes, by \(0.035\%\) or 35 parts in 10,000, which, of course, is a negligible quantity for 0.1\% precision work. This coil did not exhibit any further rise of resistance, and after 45 minutes the test was discontinued. Meanwhile, the temperature coil was slowly responding—then rapidly, and, afterward, very slowly, until, at last, it had crept up nearly 0.8\%, corresponding to a temperature rise of between one and two degrees Centigrade. At the same time, the current-carrying coil (of German silver) had crept up 0.35\%, corresponding to one degree Centigrade. The difference between the two is chargeable to the errors of observation.

It is but the equivalent of a fraction of one degree, and the temperature coil may quite
possibly have received some increase from the
room, not recorded on the Thermometers placed
on the test table. The result serves to
show how successfully the design accomplishes
the purpose of ventilating the coil, and
indicates, in a general way, the quick and
thorough transfer and equalization of heating
effects between adjacent coils.

The Temperature coil, it will be remembered,
was of Copper wound next to the experimental
German Silver coil on the same frame and
arranged precisely like the other.

Little more remains to be said.
The design not only accomplishes the primary
purpose of reducing and equalizing the
various heating effects among the coils of
the bridge, but, also, presents the
advantages of cheapness, in first cost and
simplicity of construction, as claimed above,
in the earlier pages of this report. Though planned
for coils of ample gauge numbers, it is extraordinarily compact and light.

The arrangements of the plug-contact-blocks and keys are exceptionally convenient, and novel features are introduced to lessen materially all chances of making mistakes in "reading" the plugs.

Though its dimensions are now less than those of the average Land-Camera, it might easily be reduced by nearly one-half of its present cubic contents, except that, in such small dimensions, the difficulty of keeping the insulation high might be prohibitive.

In fact, as a portable resistance-box, it is, perhaps, premature, for I know of no portable galvanometers of sensitiveness commensurate with the precision of measurements which these ventilated coils appear to be capable of yielding.
- In explanation of the accompanying drawings-

- All figures drawn full size -

- Dimensions of model agree with drawings.

Figures 1 is a plan of the wooden
tape piece into which the ebonite
slab fits.

Figures 2 & 3 are cross-sections taken
in the planes marked a.b.c.d,
respectively, showing thickness of walls
and method of supporting the ebonite.

The ebonite is shown cross-hatched
according to the usual convention.

Figure 4 shows the size of the dies
of ebonite threaded onto the 6 ebonite
rods to form the open work frame
for supporting the candles.

Figure 5 is cross-section of same.

Figure 6 is a front elevation of a
fragment of the frame.
Figure 7 shows a form of ebonite punching adapted for four rods and intended for use in the 5- and 6-dial bridges, also in places where better ventilation is required.

Figures 8 & 9 are section and front elevation of this type of frame.

Figure 10 shows the method of attaching the frames to the wooden supports and also shows the angle irons which fasten the supports to the top piece.

Figure 11 is an elevation of the open end-piece, showing the method of holding the terminal block.

Figure 12 is a plan of the top of this end-piece showing the removable retaining-piece for the terminal block.
Figure 13 is a cross-section of this end of the box, taken down through from top to bottom, and showing the ebonite terminal block in position — with brass terminal screw in place, also showing a fragment of the ebonite top-piece as in Figure 2.

Figure 14 is a plan of the ebonite top-piece, showing arrangement of plug-contact blocks and position of galvanometer and battery keys.

Figure 15 is an elevation of same, taken from the rear, showing the under-cutting of the contact-bloks and height of keys and plugs.
Figure 16 shows,
at the left of the vertical centre line
a section of the box cut through the
plane -ab- of Figs 1 and 14.
At this plane the back row of coils
appears in elevation and the walls of
the box are in section, while the
terminal and contact pieces are
part section and part elevation.
At A/B are shown wooden cleats into
which the upright supports of the coil-
frames fit to steady them against
accidental jarring. At C on the
right-hand half of the figure is shown
the alternative scheme of pinning the
support to make a secure combination.
Fig. 10 also shows this. In the model,
both pins and cleats are used.
Only two of the connecting wires from the
plug-contact blocks on top to the bobbins
are shown sketched in, at D. The other
are omitted for the sake of clearness. They come so close together as to confuse the drawing if shown altogether. The binding-posts are shown in section, and the method of securing metallic connection between the posts and the blocks on the ebonite top-plate is also indicated at E.

On the right of the central line is shown an elevation of the box partly cut away.

Figure 17 shows the dimensions of one of the slide-doors.

Figure 18 gives the disposition of the binding-posts on the end-plate and shows how to connect galvanometer (lettered G), battery (lettered B) and the unknown resistance (lettered X).

Figure 19 gives the connexions of the box, figure 18 being transferred thereto and indicated by the four black circles.
The photographs also show, in addition to the various features already pointed out, the ornamental cover, into which the rows of idle sockets are fitted.

To the model, I have also added an ornamental base, which is not shown in the working drawings.