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THE FUNDAMENTAL BASIS FOR THE STANDARDIZATION OF ELECTRICAL INSTRUMENTS AND METERS

by

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By its organic act, the functions of the National Bureau of Standards "shall consist in the custody of the standards; the comparison of the standards used in scientific investigations, engineering, manufacturing, commerce, and educational institutions with the standards adopted or recognized by the Government..... the testing and calibration of standard measuring apparatus......" It is the purpose of this circular to describe in some detail how this function is carried out as regards the standards used by the electrical power industry for the measurement of the electrical quantities.

The accompanying diagram shows schematically the chain of measurement by which the true value of each working standard is derived from other standards of a more fundamental character. In this diagram the blocks with light borders correspond to specific standard instruments or types of apparatus used at the Bureau in its testing work. The blocks with heavy borders represent the various types of standardizing measurements. Most of these measurements are made on apparatus submitted by the public as well as on the working standards of the Bureau. They show the kind and range of tests which the Bureau is equipped to carry out regularly for other laboratories.

By international agreement and in conformity with Public Bill No. 105, of July 12, 1894, the electrical units are defined as those of the "absolute practical" or "meter-kilogram-second" system. Their values are established by absolute measurements which serve to fix the relation between the electrical units and the more fundamental mechanical units of length, mass, and time. Such absolute measurements are a normal function of the larger national standardizing laboratories, but are seldom made elsewhere both because of their technical difficulty and because adequate accuracy can be obtained by having secondary standards tested at the national laboratory. The apparatus and processes used in such absolute measurements are indicated by the six blocks at the top center of the diagram.

The first step in establishing the ohm by absolute measurement is the construction of an inductor (either mutual- or self-) the dimensions of which can be measured with great accuracy. From these dimensions and the permeability of the space surrounding the winding the value of the inductance in absolute henries is calculated. A further experiment is then performed in which a resistance is measured in a circuit at a known frequency in terms of this inductance, thereby establishing the value of the resistance in absolute ohms.

To establish the unit of electromotive force, the first step is the construction of a current balance, of accurately known dimensions. The electrodynamic force developed by the current circulating in the coils of the apparatus is balanced by the force of gravity on a known mass. From this force, together with the measured shape and relative position of the coils, the value of the current in absolute amperes can be calculated. A resistor in series with the coils, and therefore carrying the same current, is adjusted until the IR drop in it just balances the emf of a standard cell. The emf of the cell in absolute volts is then equal to the product of the value of resistance in absolute ohms and the calculated value of current in absolute amperes.

During the intervals between successive absolute measurements, the units of resistance and of electromotive force are maintained by primary groups of carefully constructed standard resistors and cells. Usually 10 resistors and 25 cells are included in these groups. Each standard is compared directly with the working standard used in the absolute measurement, and thereby a value in terms of the absolute unit is obtained for each member of the group and for the mean of all. Frequent later intercomparisons are made between the individual standards in each group so that any developing defect, drift, or unsteadiness in any one standard is detected as a shift in its value relative to the mean. If this should occur, another standard of high quality would be substituted for the defective one and the assigned value of the mean adjusted to correspond. The value of one of the standards in the group used as a reference is assumed to remain constant between intercomparisons, and the mean value for the whole group is assumed to be constant over the longer interval between absolute measurements.

Normally, as an additional check, international intercomparisons are made every few years at the International Bureau of Weights and Measures at Sevres, France. There, standards sent by each of the large national standardizing laboratories are compared with one another so that each national laboratory may know how well its units of resistance and electromotive force agree with those of the other countries.

Measurements of resistance standards are based on this group of precision resistors and can be made by use of a precision bridge and carefully calibrated ratio sets (shown in the 4th row of the diagram) to a relative precision of one part in ten million although the accuracy of the absolute measurements by present methods is probably not as good as 20 parts per million. A resistance ratio of 10 to 1 also can be set up with this accuracy and used to step up and down successively so as to fix the values of precision resistance standards over the range from 10,000 ohms to 0.0001 ohm. Tests of standard resistors, resistance boxes, bridges, and potentiometers of various types are made by the Resistance Section on the basis of these standards. With the NBS Standard Cell Comparator the emf's of two standard cadmium cells can be compared within one-tenth microvolt. This device is used by the Electrochemistry Section in the routine standardizing tests on unsaturated standard cells. By such means a large number of the electrical laboratories throughout the nation establish the values of their reference standards.

In addition, many laboratories send for test high grade laboratory standard ammeters, voltmeters, and wattmeters, and many utility companies, particularly those in nearby areas, send their portable standard watthour meters. Such instruments and meters, and their range-extending apparatus, which form the basic standards of these laboratories, are tested in the Electrical Instruments Section, and these tests serve in effect to transfer the electrical units to the respective laboratories.

The work of the Electrical Instruments Section is, of course, closely parallel in many ways to the work carried on in the laboratories of certain state public utility commissions as well as in those of the larger electric manufacturing companies and public utility companies The methods used may seem cumbersome and slow when compared with those used in certain commercial laboratories. The conditions at the Bureau are, however, different in some respects, in particular because of the relatively smaller volume of testing work to be done, the greater variety of types and ranges of apparatus submitted for test, and because usually a materially higher precision is sought. Since the Bureau is a court of last resort, the Bureau laboratories must, by duplication of measurements and standards and in all other possible ways, take pains to eliminate sources of systematic error. As in any other business, one can secure insurance only by paying a premium, and in this case the premium paid to insure accuracy is an increased expenditure of time and labor.

The precision resistors shown at A and the unsaturated standard cells shown at A' constitute the working standards used daily in this testing of indicating electrical instruments and meters. The junction at B symbolizes (1) the use of a potentiometer with a standard resistor (or shunt) to measure current and to test ammeters; (2) its use with a volt box to measure higher d-c voltage and to test voltmeters; and (3) its use with both to measure d-c power and to test wattmeters. Of course, for economy this last type of test is normally made by using separate sources of current and of voltage. The transfer from direct to alternating current, voltage, and power by the use of transfer instruments of the electrodynamic type occurs at C, and the combination of power and time to give values of energy occurs at D.

It will be noted that as this main stream of measurement proceeds and builds up standards for other quantities, various types of auxiliary apparatus contribute additional possibilities to it and continually increase its breadth and scope. Thus the standard volt box has within itself means for fixing voltage ratios over a range of 3000 to 1, and thus extends the voltage range correspondingly. The standard resistors for current measurements are constructed so as to have very nearly the same resistance when the current which they are carrying is large as when it is small, and thus correspondingly extend the range of current measurement. The transfer instruments of the electrodynamic type are carefully constructed so that they contribute the property of having the same torque, and therefore reading, on alternating current as on direct current, at least up to several hundred cycles per seccond.

The non-inductive standard resistors which are used in the a-c potentiometric method shown at G for testing current transformers are so constructed as to have the same effective resistance on alternating current that they have on direct current. A comparison of the residual inductances of these resistors with those of 4-terminal standards of phase angle, which are of such shape that their phase angle can be accurately calculated from their dimensions, serves to fix the inductances as well as the resistances of the "non-inductive" standards. Experience has shown that grave difficulties enter if one attempts to trust the performance of such non-inductive standard resistors above 2500 amperes; consequently the further extension of the range is obtained by the use of the standard multiple-primary current transformer. This transformer possesses the properties of having a ratio which varies strictly in proportion to the number of primary turns even when the number of primary turns is varied by a factor as great as 24, and of having its phase angle substantially independent of the number of primary turns.

In the high voltage field, we have in similar fashion an increase in range contributed by the use of the shielded resistance potential divider, which is used in the a-c potentiometric method shown at H for testing voltage transformers. This is so constructed that its elements have the same effective resistance and inductance when connected in series as they have when tested alone, and it therefore serves to step the known voltage range up to 30,000 volts. Here again difficulties arise in further extending the range by this method and again the use of standard multiple-primary transformers, which can be calibrated with their primary coils in parallel and used with these coils in series, serves to step up the range by a further factor. In the high voltage laboratory a group of such multiple-primary transformers are available to step the range up to a maximum of 250,000 volts. These calibrated voltage transformers also serve as working standards of ratio and of phase angle with which other voltage transformers can be readily compared. The Brooks absolute high voltage electrometer, of the attracted disk type, serves to give an independent check on the measurement of high alternating voltage. It has confirmed our standard method to 0.01%.

As shown on the diagram at J, the measurement of time intervals rests fundamentally on the astronomical work of the Naval Observatory. These observations serve to give the true value to be assigned to the frequency of certain crystal oscillators maintained by the Radio Division of the Bureau. Subharmonics of these oscillators are used to give time signals in the form of short pulses spaced at intervals of exactly 1 second or in the form of a continuous alternating current of exactly 60-cycle frequency. The first form of signal is used with a relay system to close the voltage circuit of a watthour meter under test automatically at the beginning of one second and, after a predetermined interval has elapsed, to open the circuit at the beginning of another second. The second form of signal is used to operate timers driven by synchronous motors, started and stopped manually to record the time required for the watthour meter under test to make a counted number of revolutions.

As one passes down the stream of measurement from the fundamental standards, which can be intercompared with an accuracy of a few parts in 10,000,000, the accuracy of the measurements necessarily diminishes. It is, however, greater than that needed for testing portable and laboratory standard type instruments to the full accuracy with which their indications can be read. The uncertainty in determining the ratio and phase angle of the instrument transformers is only a few parts in 10,000 in ratio and a few tenths of a minute in phase angle. These accuracies meet the demands for practically all applications and are great enough to detect occasional minor changes or drifts in the performance of transformers which result from changes in temperature and in the magnetic condition of the core.

A distinction should be noticed between transfer testing of a-c ammeters, voltmeters, and wattmeters at E and the a-c testing at F. In the transfer test the instrument under test and the standard transfer instrument are so connected as to respond to the same current, voltage, or power. With alternating current on both instruments this is adjusted until the instrument under test comes to the desired scale point. The standard instrument is then read. Direct current is then applied to both instruments and again adjusted to give the same reading on the instrument under test. The direct current is then reversed and a third reading made, then a fourth reading is taken with alternating current again applied to both instruments. By repeating this cycle of measurements, a series of sandwiched a-c and d-c readings is obtained and the difference between the mean of the a-c and that of the d-c readings of the standard instrument is computed from these data. This procedure very completely eliminates all sources of error such as heating, shift of zero and reading error of either instrument, and leaves in the net difference only those errors which arise from sources such as inductance, capacitance, and eddy currents, in which the effect on alternating current differs from that on direct current. The transfer instruments have been carefully studied and any such effects in them are small and definite and can readily be allowed for. The net error of the instrument under test on alternating current relative to its performance on direct current is thus determined. The accuracy in such measurements approaches 0.02%.

In a straightforward a-c test the transfer instrument is first calibrated by applying direct current to it only. It is then used as a standard and the readings of the instrument under test are compared with it and at the conclusion of the measurements at each scale point the standard is again calibrated on direct current. This procedure has to be used when the a-c instrument is of such nature that it does not respond to direct current, and with all instruments the range of which exceeds the range (10 amperes, 300 volts) of the standard transfer instruments, because in this latter case instrument transformers have to be used to extend the range. It will be noted that any self-heating or zero shift of the instrument under test which occurs in the course of the straight a-c test will be included in the final result and the accuracy of a test of this type is therefore definitely less than that of the transfer test. Many laboratories are equipped with potentiometers and standard cells, and can determine the d-c performance of their instruments for themselves. In such cases it is evident that the transfer test, because it gives additional information which such laboratories are generally not in position to determine, is the more desirable test to have made on reference standard instruments.

Shunts used in the measurement of large direct currents are frequently sent to this Bureau for test, and as indicated on the diagram their resistance while carrying a large current can be measured by using the Kelvin double bridge and the precision resistors of large current-carrying capacity. It should be pointed out that heavy-current shunts fall into two classes. Certain ones (unfortunately only a few) may be called thermally self-contained and are so designed that the heat generated within them by the current is dissipated in a definite manner by oil or forced air cooling or in some other way, which is independent of the current leads which connect the shunt in the circuit. In such a case the resistance of the shunt is a definite function of the current, the ambient temperature, and the temperature of the cooling medium. A test of such a shunt can well be made under conditions which very closely duplicate those under which the shunt will be used, and the resulting measured value of resistance is definite and reproducible. However, in many designs it is expected that a considerable part of the heat generated within the strips of resistance alloy will be dissipated by conduction along the current-carrying leads. Furthermore, if the contact between the current terminals and the bars leading to the shunt is not good, the heat generated at this contact may be of a magnitude quite comparable with the heat generated in the resistance alloy itself. The temperature, and therefore the resistance of such a structure, necessarily depends upon the quality of the current contacts and the nature and dimensions of the conductors connecting it to the circuit. It is therefore quite impractical for the testing laboratory to duplicate all of these vital conditions and there is little merit in attempting to test such a shunt with full rated current. The usual procedure in this latter case is to measure the resistance of the shunt at two or three different temperatures which are obtained by enclosing the shunt in a separately heated chamber with temperature control and to use in test only enough current to give good sensitivity in the measurement. If the customer will then observe the temperature which the shunt attains when in use in his circuit, he can obtain a fairly reliable value for its resistance by interpolating between the values obtained in the enclosure.

By law, the National Bureau of Standards is required to charge fees* for tests other than those for branches of the state or federal governments. The fees are set to cover the cost of the services rendered. Thus they are high enough to avoid subsidized competition with private testing laboratories. but are low enough to avoid penalizing any reasonable effort to obtain high accuracy. Copies of the fee schedules and instructions for specifying the desired tests and for details of shipment can be obtained from the Bureau upon request.

One point which should be emphasized is that the National Bureau of Standards is not a repair shop. When any measuring instrument shows signs of trouble, it should be sent first to the manufacturer for repairs before being sent to Washington for test. If, as occasionally happens, some defect develops in the course of a test at the Bureau, the customer is billed for the testing which has been done prior to the discovery of the fault, as well as for the complete test when the instrument is later returned after it has been repaired by the manufacturer.

In addition to the types of electrical testing described here, the Bureau regularly tests for the public resistors ranging in value from 1 microhm to 100 megohms, inductors from 10 microhenries to 10 henries, and capacitors from 0.01 micro-microfarad to 10 microfarads. Tests are made on standard magnetic specimens to determine normal induction and hysteresis curves on d-c and also a-c permeability and core loss.

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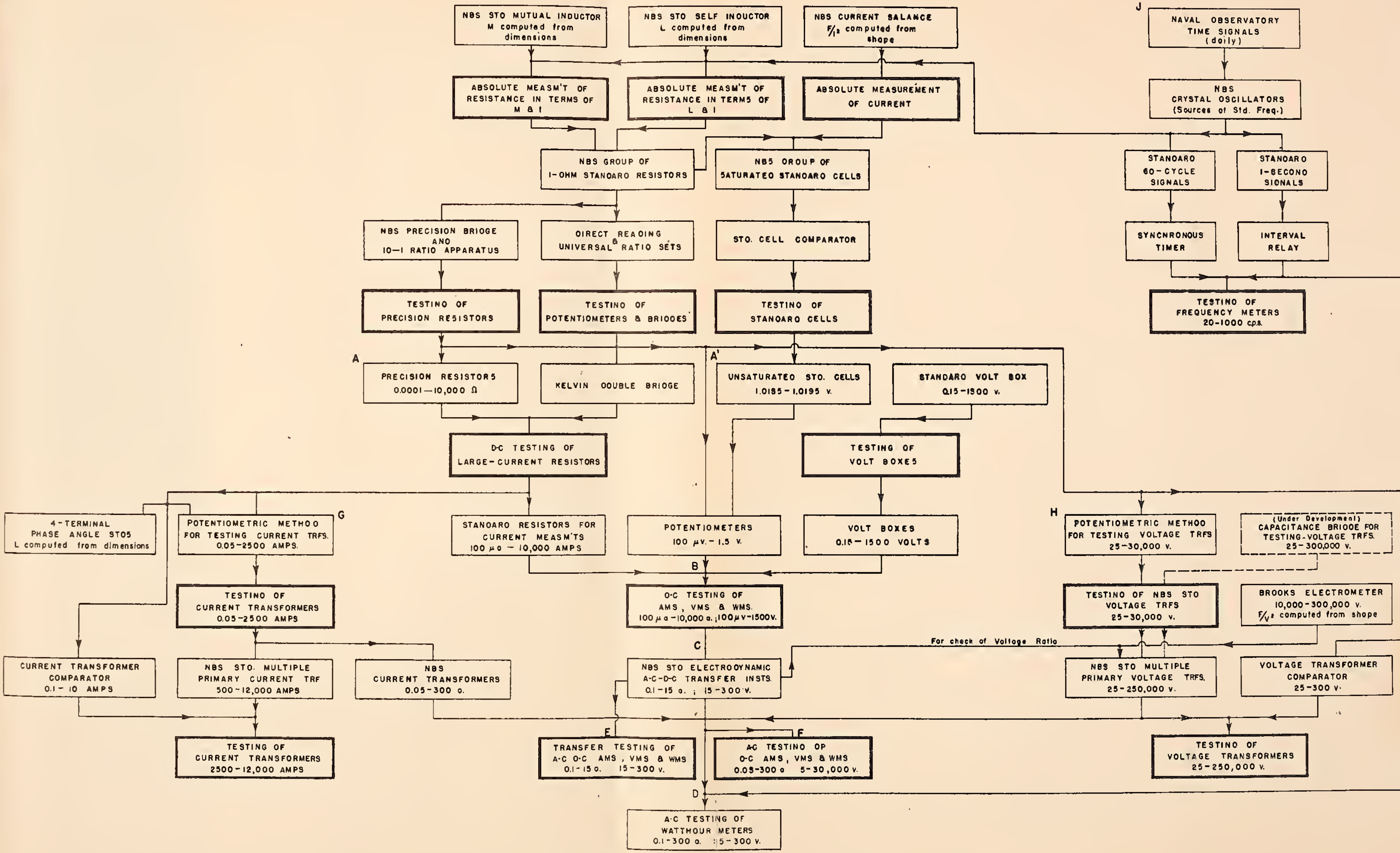
*Further information concerning the testing of electrical instruments is given in NBS Letter Circular 475 and in test fee schedules 131 to 1312, inclusive.

Also the Bureau carries on a large amount of rather routine electrical testing for other agencies of the federal government, including qualification tests of dry cells and of electric lamps and acceptance tests of insulating materials and devices. This work, however, is done only for other branches of the federal government. Such insulation tests require no great accuracy and do not result in the dissemination of standard values. Hence the making of such tests by this Bureau for outside parties would constitute an unnecessary competition with private laboratories. The National Bureau of Standards also carries out from time to time tests of other types of electrical equipment such as fuses, small circuit breakers, relays, insulated wire, etc., but this work also is done only for other branches of the government. A growing feature of the electrical work of the Bureau is that undertaken in cooperation with technical committees of the American Institute of Electrical Engineers and other standardizing bodies with a view toward developing and standardizing methods for making tests and measurements.

FACILITIES FOR TESTING ELECTRICAL INSTRUMENTS AND METERS AT THE NATIONAL BUREAU OF STANDARDS



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