Apparatus with which NBS studies "artificial lightning"—very short-duration surges of high voltage and intense current used to test high-voltage equipment. At right is 2,000,000-volt surge generator, for which improved voltage-measuring circuits are being developed. The large transformer in the background (with smooth tank) has voltage ratings of 125,000 and 250,000 volts. It is calibrated with its primary windings in the exact ratio of the instrument transformers submitted for test. The two large transformers (center), rates at 350,000 volts, serve as a supply for the measuring circuit and for other 60-cycle tests.

STANDARDS FOR ELECTRICAL MEASUREMENT

By Francis B. Silsbee

Precise electrical measurements are of fundamental importance to modern science and industry. This is true not only in the communication and power fields but in many other areas where the flexibility and convenience of electrical methods have made them almost indispensable for the measurement of nonelectrical quantities. Thus, while in textbooks energy is defined simply in terms of force and length or of mass and velocity, in actual practice the heat energy of fuels and the energy output of prime movers are universally measured to high precision by electrical methods. Likewise, the basic electrical units enter into the determination of nearly all the fundamental atomic constants, as well as into daily measurements of heat, light, color, strain, acceleration, displacement, and chemical properties.

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Effective application of electrical equipment and measurement methods requires uniformity to a high degree of precision in the basic electrical units. Some two billion dollars' worth of electrical machinery and apparatus is manufactured annually in this country. Were each manufacturing company to use an even slightly different value for the volt or the ohm, the apparatus made by its subcontractors would fail to function properly as a part of the final product. The result would be an impossibly confused situation, causing large financial losses to the Nation. In the communications industry, the multiplex transmission of intelligence over a relatively small number of circuits is dependent on the precise adjustment of capacitance, inductance, and other circuit components in such a way as to prevent the signals from straying into the wrong channels. This, again, requires precise uniformity in the measurement of the basic electrical units.

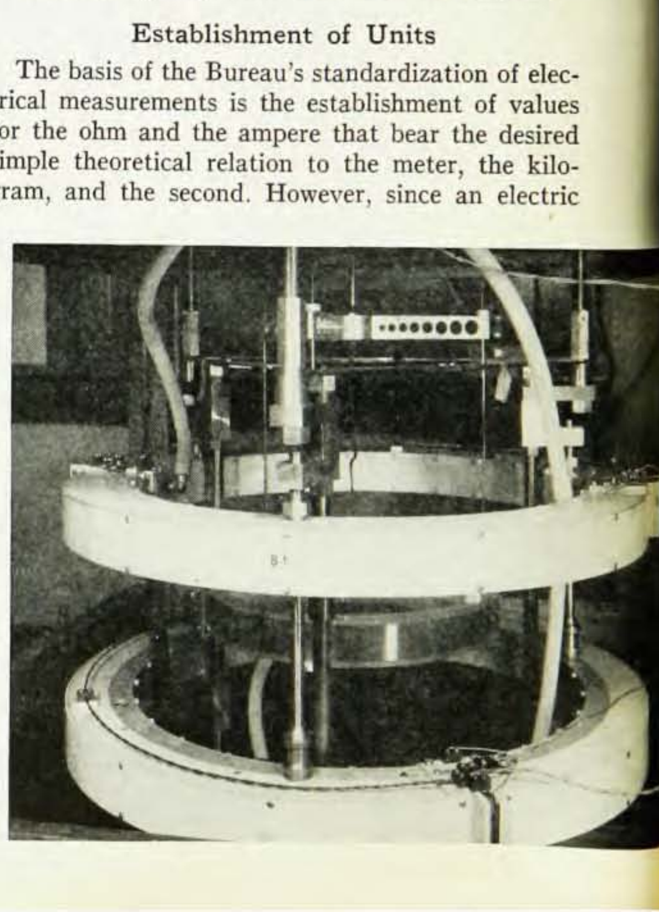
As the custodian of the national standards of physical measurement, the National Bureau of Standards has the responsibility of insuring that the units of measurement used in science and industry are constant through the years and uniform throughout the Nation. The Bureau has developed very precise standards of resistance and voltage whose values are established by absolute measurements that fix the relation between the electrical units and the fundamental mechanical units of length, mass, and time. From these basic absolute electrical standards, the Bureau has derived other standards for all electrical quantities in use today.

Because of their technical difficulty, precise absolute measurements are carried out only in the national standardizing laboratories of a few of the larger countries. Sufficient accuracy in science and industry is obtained through accurate comparison of the secondary or working standards of other laboratories with primary standards thus calibrated. In this country such comparisons constitute the Bureau's calibration service. Each year a stream of about 2,000 high-grade electrical instruments, standard cells, and other measuring apparatus flows through the Bureau's electrical laboratories. The services performed range from the comparatively simple measurement of the emf of a standard cell to the determination of the ratio and phase angle of a multirange current transformer at several frequencies, currents, and loads, which may require 1000 separate measurements. Among the devices submitted are potentiometers, bridges, resistance boxes, volt boxes, capacitors, inductors, multimegohm resistors, instruments and meters of all kinds, precision shunts for large currents, instrument transformers, standard magnetic test bars, magnetic test coils, and standard cells of both the saturated and unsaturated types. They come from manufacturers of electrical equipment, from public utility companies wishing to make sure that their charges are correct, from public service commissions which regulate the utility companies, and from communication laboratories, university laboratories, private commercial testing laboratories, and the many scientific laboratories of the Federal Government.

The demands of modern science and technology have made this work more and more exacting, not only as regards accuracy, but also in the range of values and variety of units in which measurements are made. Thus the Bureau now measures precisely currents, voltages, and resistances having values up to tens of thousands of amperes, hundreds of thousands of volts, and millions of billions of ohms. This is done with direct current, with alternating current of various frequencies up into the thousands of megacycles per second, and with surges of current lasting only a few millionths of a second.

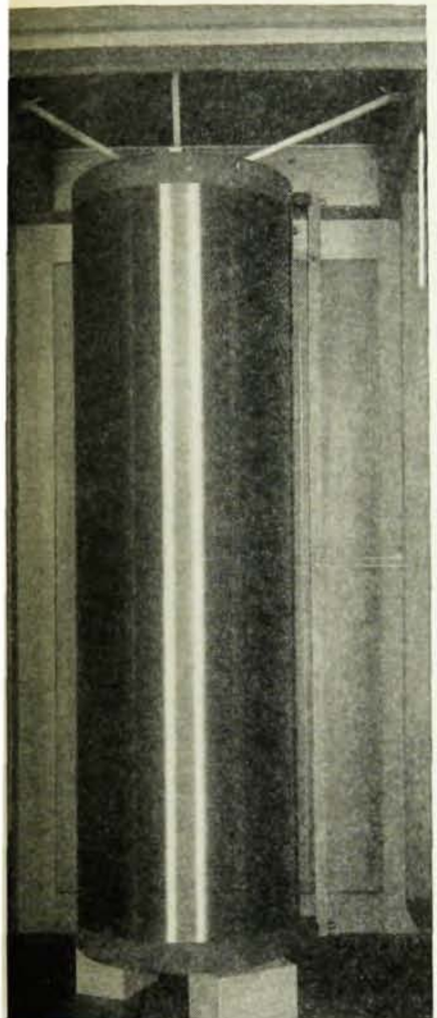
Establishment of Units

The basis of the Bureau's standardization of electrical measurements is the establishment of values for the ohm and the ampere that bear the desired simple theoretical relation to the meter, the kilogram, and the second. However, since an electric



Coils of current balance used to "weigh" current for the absolute determination of ampere. Smaller coil is suspended, coaxial with two larger coils, from the pan of a sensitive balance. When current flows through all three coils in series, the mechanical force between the small and the large coils is measured with the balance. From the value of this force and the mechanical dimensions of the coils, the absolute value of the ampere is computed.

current is by its nature evanescent, the volt, derived from the absolute ampere at the time the latter is measured, is embodied in the calibration of a group of standard cells which together with the standard resistors embodying the ohm are kept as permanent primary standards.



Self-inductor (above) permits NBS scientists to determine the ohm in absolute measure to an accuracy of a few parts in a million. The 1000 turns of the coil are wound in a lapped helical groove on a Pyrex glass form about 35 mm in diameter and 1 meter long. The diameter and average pitch of the coil have been measured to one part in a million. Its inductance is 103 millihenries.

The determination of the ohm consists of two steps. The first is the construction of an inductor (either self or mutual) which is so designed that its essential dimensions can be measured mechanically with high accuracy and which is of such a shape that the inductance can be calculated from these measured dimensions. Both self and mutual inductors have been prepared at the Bureau by winding wire in lapped helical grooves on forms of glass, quartz, or porcelain. The second part of the process consists of an electrical experiment in which a bridge or equivalent circuit is used to compare the reactance of the inductor at a known frequency with the resistance to be measured. When the resistance in absolute ohms of the resistors used in the bridge circuit has been determined in this way, the absolute resistance of other standard resistors can be found by comparison.

A current is measured in absolute amperes by determining the mechanical force between two parts of the circuit in which it flows. In the center of two large fixed coils, a small coil is hung from the arm of a precision balance. All three coils carry the current to be measured, but the current in the fixed coils can be reversed. The small electromagnetic force developed by the current in the coils tends to pull the movable coil downward for one direction of the current in the fixed coils but tends to lift it when this current is reversed. From the change in the force on the balance when the current is reversed and from the measured dimensions of the coils, the value of the current in absolute amperes can be computed.

A second feature of this experiment makes use of the standard current while it is being "weighed" to measure directly the emf of a standard cell in absolute volts. This is done by arranging the standard cell so that its electromotive force is exactly balanced by the drop of potential produced in a known resistance by the standard current. The emf of the cell is then computed by Ohm's law.

A group of 25 standard cells and a group of 10 carefully constructed 1-ohm standard resistors serve to preserve the values of the volt and of the ohm from day to day and from month to month. The various members of each group of standards are intercompared at intervals of a few months; and as long as their relative values are constant, it is assumed that the absolute mean value of the group has also remained constant. If an individual standard is found to have drifted relative to the others in its group by a significant amount since the previous intercomparison, it is rejected and replaced by another standard which has a good record of performance. The process of comparing a resistor with the standard mutual inductor is so convenient that it is frequently used as an independent check on the constancy of the group of standard resistors. However, the mechanical measurement of the dimensions of the inductors and of the current balance is so very tedious and time-consuming that this experimental work is carried through only once in a decade as the final check on the constancy of both types of standard.

From the standard ohm and the volt thus maintained at the Bureau, the other electrical and magnetic units are derived by a variety of experimental procedures. The farad is precisely obtained by charging and discharging an air capacitor at a known rate in a Maxwell commutator bridge. The henry is determined by comparison with capacitors and resistors in a Maxwell-Wien bridge. The ampere is reestablished, when desired, by measuring with a potentiometer the drop it produces in a known resistance. The ampere and the volt are combined to give the watt, and the joule and kilowatt hour are derived by maintaining a known number of watts in a circuit for a measured length of time. The gilbert and the oersted are computed from the number of ampere-turns used in magnetizing a magnetic test specimen in a permeameter of known geometry. The gauss and maxwell are obtained from the deflections of a ballistic galvanometer which, in turn, is calibrated by reversing a measured current in a known mutual inductor.

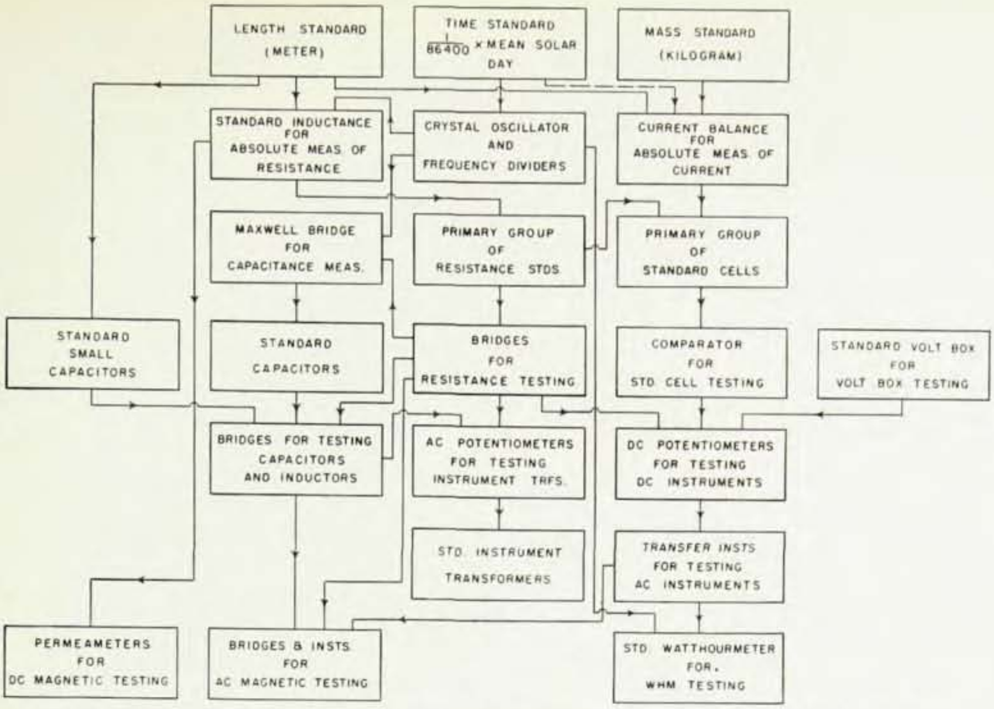
Extension of Ranges

The extension of the scale of measurement of any of the electrical quantities to other ranges is based, in large part, upon the establishment of a ten-to-one ratio in a special, highly accurate bridge. By successive application of the ratio, resistances as low as 0.00001 ohm or as high as ten million ohms can be accurately measured. Still higher resistances up to 10^{18} ohms are measured by more complex methods, such as the determination of the rate of accumulation of charge in a known capacitor. Inductance and capacitance measurements are extended over wide ranges by means of ratio arms of known resistance ratio. However, determination of standard capacitances below 1 micromicrofarad is based upon an independent set of measurements involving the construction of air capacitors of such shapes that their capacitance can be computed precisely from their dimensions.

Direct currents as high as 10,000 amperes are measured with a potentiometer and standard resistors of low value so constructed that their temperature and resistance are not affected by the very considerable heat developed when large currents are used in them. Direct voltages up to 1500 volts are measured by means of potential dividers, or volt boxes. The ratios of the dividers are derived by connecting in series groups of resistors whose relative individual values have been found by substitution methods. Specially constructed resistors, shielded to avoid corona discharge, are used in x-ray testing to measure dc potentials as high as 1,400,000 volts. In the upper part of this range additional shields separately maintained at appropriate intermediate potentials are required.

The great bulk of the electrical energy generated and utilized throughout the country is distributed as alternating current. The step from the direct current standard cell to ac measurements of voltage, current, and power is therefore of fundamental importance. For 60-cycle work, the transfer is carried out by means of two specially constructed astatic electrodynamic instruments, a wattmeter and a voltmeter. In these instruments the moving coils are supported by taut strip suspensions, and the position of the moving coils is indicated by a spot of light on a scale at a distance equivalent to a pointer 13 feet long. The wattmeter has been carefully compared both with a quadrant electrometer and with the loss in a capacitor which had been tested in a Schering bridge; such measurements have established the accuracy of the two electrodynamic instruments at frequencies up to 3000 cycles. Directly or indirectly, the accuracy of practically all the ac instruments used in the transmission of electrical energy depends on these two standard instruments. For tests of ammeters and voltmeters at 400 cycles and above, transfer circuits employing thermocouples are also used.

In commercial practice the range of alternating current is extended upward from five amperes by means of calibrated current transformers. Thus, an important part of the Bureau's calibrating service consists in the calibration of standard current transformers which, in turn, are used by manufacturers and electric utility companies to calibrate their working transformers. Special four-terminal standard resistors, constructed so as to have negligible skin effect and a known computable inductance (hence a known phase angle), are used to measure the ratio and phase angle of transformers up to 2500 amperes with a specialized form of ac potentiometer. Beyond this limit, up to 12,000 amperes, the unknown transformer is compared with a multirange standard transformer, which is cali-



Block diagram showing steps used by Bureau in deriving precise values for all electrical units from basic mechanical units of length, mass, and time.

brated on its lower ranges by the use of standard resistors and is then used as a standard on its higher ranges. Careful study of this standard transformer has given assurance that its various ranges bear simple integral ratios to one another.

Similarly, the extension of the ac voltage scale above 150 volts is, in practice, based upon the use of voltage transformers. A special shielded resistor, capable of operating at 30,000 volts, is used to measure the effective ratio and phase angle of voltage transformers up to this limit and also to check the performance of standard multirange transformers when they are connected for 25,000 volts. These multirange transformers can then be connected for 50,000 or for 100,000 volts and used as standards at these latter ratings. A still larger standard transformer is calibrated with its coils in parallel at 100,000 volts and used with its coils in series as a standard up to 250,000 volts.

For all this testing and calibration work, other than that performed for the Federal and State governments, the law requires the Bureau to charge an appropriate fee. These fees are high enough to avoid subsidized competition with private testing laboratories but are low enough to make it possible for all industrial laboratories to attain high accuracy where desirable in their work. In any event, the cost to both government and industry of the Bureau's electrical standardization services is slight in comparison with the savings to the Nation which result from the program. For example, the electrical power industry has now grown to the point where the annual bill for electrical energy is approximately four billion dollars. If there were a consistent error of 1 percent in the standards used at the Bureau to calibrate the electric meters with which the industry calibrates its customer meters, either the power companies or the consumers would lose 40 million dollars each year. Yet the cost of maintaining the Bureau's service in this field is much less than 1 percent of the discrepancy.

The Bureau is currently making efforts to meet the demand for ever increasing volume and complexity in electrical standardization work. Techniques are being developed for the more accurate measurement of man-made lightning—very short-duration surges of high current—which are coming to be used by electrical manufacturers to test high-voltage equipment. Methods are also being worked out for the more rapid and economical checking of watthour meters; the testing of the very high resistances now used in measuring ion currents and other radiation effects; and the testing at 400 and 1000 cycles per second of instruments and instrument transformers for use on aircraft and in induction furnaces for heat-treating metals.