THE FOURTH KELVIN LECTURE.

THE OHM, THE AMPERE, AND THE VOLT : A MEMORY OF FIFTY YEARS, 1862–1912.

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(*Delivered 27th February*, 1913.)

My first words must be to express my thanks to you, Mr. President, and to the Council for your renewed invitation to deliver this lecture, to fulfil the welcome task of speaking to an audience which realizes very fully all we owe to Lord Kelvin, of some small portion of his work.

I cannot claim the many-sided knowledge of that work possessed by the first Kelvin lecturer—the distinguished author of his biography—nor the intimate acquaintance with detailed portions acquired by one who, like Sir Alfred Ewing or Professor du Bois, had worked under him in his own laboratory ; but for years I was his disciple and friend. May I recall some personal memories ?

I began to work at practical physics in 1876. The Cavendish Laboratory had not long been opened. Maxwell was equipping it with new apparatus, and almost my first task was to trace the behaviour, under various rates of discharge, of a battery of large tray Daniell cells designed by Thomson. The instrument given me to measure the E.M.F. was one of the large-pattern White quadrant electrometers with the mouse-mill replenisher. It had to be set up and adjusted, and for a novice the task did not prove easy. We were not fed with a spoon by Maxwell, but fortunately I had no examination in view. Since that time I have shunned the instrument and felt a holy reverence for its designer.

Again, a few years later with various friends I went to Largs after a British Association meeting. I had recently become Secretary of the Electrical Standards Committee. While we were there a parcel arrived from America which proved to be one of the first concave gratings sent to England, and I was told off to set it up in the drawing-room after dinner. The slit was a narrow cut in a visiting card. It stood on the piano in front of a spirit lamp with a salted flame. The grating was placed on the mantelpiece, and a circle on which the images lay was roughly marked out on the floor with footstools and cushions. The party was set to work to find the D lines. Those of the first two orders were seen by all. "We were delighted with the result :

I had never seen anything like it before," wrote Sir William in a letter to Professor Mendenhall.

Again, a little later, he was in Cambridge, and I met him at dinner at Professor Stokes's house. He was very full of ether theories, and specially interested in a labile or contractile ether whose properties he had recently described in the *Philosophical Magazine*. There were certain difficulties in the theory, and I suggested how some of these might be met. He was delighted, and took me at once to Lady Thomson and explained in his own enthusiastic way what I had done. A few days later there appeared in the *Philosophical Magazine* a note dated Train, Cambridge to Glasgow, which begins: "Yesterday evening, in Cambridge, Mr. Glazebrook pointed out to me . . . He promises a paper on the subject for the December number of the *Philosophical Magazine*."

To-day the theory of the labile ether has but little interest for any. Its films have contracted and elasticity has gone. You will understand the value of Lord Kelvin's generous appreciation to one who was just beginning to taste the pleasures of exact research and accurate experiment. From that time he was my friend until the day in the Abbey when as the representative of the Institution I was one of those who bore our greatest President to his long home and the mourners went about the streets.

A Kelvin lecturer, at any rate at present, has an ample choice of subject, and for me the selection is obvious. The volume on the table contains a reprint of the Reports of the Electrical Standards Committee of the British Association, which in great measure through the generosity of Mr. R. K. Gray have been issued to commemorate the work of Thomson and his colleagues in putting the science of electrical measurement on a firm basis. I propose to give some account of this work; to trace briefly the history of the ohm, the ampere, and the volt from the days of the first Atlantic cable, when there were no standards of resistance and the simplest applications of Ohm's law to practical problems were hardly known, up to the present time when resistances, currents, and electromotive forces are compared with an accuracy attained in hardly any other science. I shall try not to weary you with details, but I hope to impress on you the enormous debt we owe to these early pioneers whose clear-sighted vision has done so much to render possible the modern uses of electricity.

I think it was Thomson himself who compared somewhere the growth of the steam engine and the dynamo. The rapid progress of the latter depends in no small measure on the fact that the electrical quantities which occur in its theory are all capable of exact measurement, and that by an application of the fundamental laws we owe to Faraday, to Hopkinson, and to Ewing, its theory can be worked out and the results predicted with an accuracy which even now cannot be reached for the steam engine, and which until the days of Joule and Thomson was quite impossible.

Thanks to the kindness of many friends, there is on the table a most valuable collection of historical apparatus about which all of you have read but which few have seen. You know the pictures, perhaps, of Thomson's rotating coil or of Joule's first ampere balance, or of the early forms of Wheatstone bridge : here they are to be seen at least once in a lifetime by all.

The Electrical Standards Committee of the British Association was appointed at the Manchester meeting in 1861 as the result of a paper by Sir Charles Bright and Mr. Latimer Clark proposing names for the standards of resistance, current, electromotive force, and quantity. The volt was to be the standard of resistance, the ohma of electromotive force. Thomson moved for a Committee "For Improving the Construction of Practical Standards of Electrical Measurements." In its original form the Committee consisted of Thomson, Williamson, Wheatstone, W. H. Miller, Matthiessen, and Fleeming Jenkin. To these Maxwell, Siemens, Joule, and others, were added in the following year. This first Committee lasted unto 1870. Professor Carey Foster, appointed in 1867, is its sole surviving representative.

The paper by Mr. Latimer Clark and Sir Charles Bright is printed in the *Electrician*, vol. 1, p. 3, 9th November, 1861, and is very interesting reading. The comments of the Editor, in view of our present knowledge, are perhaps more interesting. Thus he writes : "To be of any general utility, however, the proposed system of measurement must necessarily be sufficiently simple and easy of application, to meet the requirements of telegraphists. Glancing at what has already been published in reference to this important subject, we fear there is some danger that a system may be devised which will be followed exclusively by the eminent gentlemen at whose recommendation it is put forward. That this would be worse than useless, in a practical point of view, need scarcely be insisted upon." And so forth ; while Latimer Clark himself, in a letter to the Editor, 17th January, 1862, writes : "The gentlemen who constitute the Committee to report to the British Association are but little connected with practical telegraphy, and there is a fear that while bringing the highest electrical knowledge to the subject, and acting with the best motives, they may be induced simply to recommend the adoption of Weber's absolute units, or some other units of a magnitude ill adapted to the peculiar and various requirements of the electric telegraph."

The units proposed in the paper were, for electromotive force, the E.M.F. of a Daniell cell, "which will probably be found sufficiently constant for this purpose" ; and, for quantity, the charge on one plate of a condenser consisting of two parallel plates 1 square metre in area and 1 millimetre apart, with air for the dielectric, when connected to the poles of a Daniell cell.

Engineers present will realize what their position would now be had these simple practical units been chosen instead of the absolute units "ill adapted to telegraphy;" and will estimate the debt due to Thomson and his colleagues accordingly.

The Electrical Standards Committee in their earlier Reports discuss —so far as measurements of resistance are concerned—two distinct questions, and it is well to keep them distinct. They state that they had first to determine what would be the most convenient unit of resistance, and, second, what would be the best form and material for the standard representing that unit. With regard to the first point, two courses lay open to the Committee, viz. to adopt the absolute system of units devised by Weber and employed by Thomson since 1851, or to take as the unit the resistance of some definite portion of a material substance, *e.g.* a column of mercury. The choice was soon made. Led by Thomson, the Committee, at a meeting at which all the members but one were present, decided on the absolute system, and the choice has done more than perhaps any other single act to simplify and unify electrical measurements throughout the world.

One word as to the term "absolute." It is used, says the Committee, " in the present sense as opposed to the word relative, and by no means implies that the measurement is accurately made or that the unit employed is of perfect construction ; in other words, it does not mean that the measurements or units are absolutely correct, but only that the measurement, instead of being a simple comparison with an arbitrary quantity of the same kind as that measured, is made with reference to certain fundamental units of another kind treated as postulates."

Weber, in his great work *Elektrodynamische Maassbestimmungen*, Part II, published in 1852, had put the matter clearly. In mechanics, he says, fundamental units are adopted only for length, time, and mass ; the units of all other quantities considered in mechanics are defined in terms of these few fundamental units and are known as absolute units. To measure a resistance absolutely is to measure it in terms of the units of length and of time.

The three electrical units, of current, electromotive force, and resistance, are connected by Ohm's law. Two of them, *e.g.* current and electromotive force, can be defined independently in terms of the fundamental units ; the third then follows naturally.

The system devised by Weber possesses another quality which the Committee had laid down as necessary. The units bear a definite relation to the unit of work, for the unit current when traversing a conductor of unit resistance does a unit of work, or its equivalent, in a unit of time. Thomson pointed this out at an early date.

For the units of length, mass, and time, the centimetre, gramme, and second were ultimately selected—the Committee first suggested the metre as the unit of length, while Weber used the millimetre—and the C.G.S. system of units was born. Thanks to this, electricians understand each other's terms throughout the world. Compare its simplicity with the confusion from which it rescued us.

The following table (see page 564), prepared by the Committee, shows the different units of resistance used in 1864 ; and some of the old standards employed before the introduction of the British Association unit, or Ohmad as it was originally called, are on view to-night.

An International Conference on Electrical Units is, even now, somewhat confusing. The President of this Institution, who by his work as secretary contributed so much to the success of the Conference of 1908, can imagine what his labours would have been if he had had to deal with the fourteen units of the above table.

TABLE I.

Description.	Name.	Absolute $\frac{\text{foot}}{\text{second}} \times 10^7$
Absolute $\frac{\text{foot}}{\text{second}} \times 10^7$ electromagnetic units (new determination)	Absolute $\frac{\text{foot}}{\text{second}} \times 10^7$	1·000
Absolute $\frac{\text{foot}}{\text{second}} \times 10^7$ electromagnetic units (old determination)	Thomson's unit ...	1·0505
Twenty-five feet of a certain copper wire, weighing 345 grains	Jacobi	2·088
Absolute $\frac{\text{metre}}{\text{second}} \times 10^7$ electromagnetic units determined by Weber (1862)	Weber's absolute $\frac{\text{metre}}{\text{second}} \times 10^7$ ...	3·015
One metre of pure mercury, one square millimetre section, at 0° C.	Siemens's 1864 issue	3·138
One metre of pure mercury, one square millimetre section, at 0° C.	Siemens (Berlin) ...	3·156
One metre of pure mercury, one square millimetre section, at 0° C.	Siemens (London) ...	3·194
British-Association unit	B.A. Unit, or Ohmad	3·821
One kilometre of iron wire, four millimetres in diameter (temperature not known)	Digney	30·40
One kilometre of iron wire, four millimetres in diameter (temperature not known)	Bréquet	32·03
One kilometre of iron wire, four millimetres in diameter (temperature not known)	Swiss...	34·21
One English standard mile of pure annealed copper wire $\frac{1}{16}$ in. in diameter at 15·5° C.	Matthiessen	44·57
One English standard mile of one special copper wire $\frac{1}{16}$ in. in diameter	Varley	84·01
One German mile = 8,238 yards of iron wire $\frac{1}{6}$ in. in diameter (temperature not known)	German mile ...	188·4

Table II, taken from the Report of the Government Committee on Submarine Cables, and printed in the first Report (p. 335), gives a comparison of the resistance of various specimens of copper and illustrates the difficulties consequent on the absence of proper standards.

TABLE II.

(All the wires were annealed.)

	Conducting Power.
Pure copper	100·0 at 15·5
Lake Superior native, not fused	98·8 „ 15·5
Ditto, fused, as it comes in commerce ...	92·6 „ 15·0
Burra Burra	88·7 „ 14·0
Best selected	81·3 „ 14·2
Bright copper wire	72·2 „ 15·7
Tough copper	71·0 „ 17·3
Demidoff	59·3 „ 12·7
Rio Tinto	14·2 „ 14·8

So far the work had been fairly simple. The absolute system had been adopted, and it was settled that 10^9 C.G.S. units of resistance was a convenient multiple of the unit for practical work, and that this should be called an ohmad or ohm; but how was a standard having this value to be realized? Of what material was it to be constructed, and when made, how was its value to be determined in terms of the unit?

The first problem was left to Dr. Matthiessen. As to the second, Weber had, in 1852, suggested various means by which the resistance of a wire could be measured absolutely, and in his paper had described the results arrived at by three methods for the resistance of a certain wire, as follows:—

Weber's 1st method ...	1903×10^8 millimetre/second
„ 2nd „ ...	1898 „ „ „
„ 3rd „ ...	1900 „ „ „

Maximum difference = 0·25 per cent.

An extreme difference of 5 in 1900 is no mean achievement for the first attempt, but the result differed by about 8 per cent from that found later by the Committee.

Thomson and Fleeming Jenkin were asked to make a new determination and construct standards each having a resistance of 1 ohm. The apparatus was designed by Thomson and built by White under his supervision. The method had been indicated generally by Weber a few months previously in his paper "Zur Galvanometrie," January, 1862, but the Committee do not appear to have been aware of this. The experiments were conducted at King's College by Maxwell, Fleeming Jenkin, and Balfour Stewart, then my predecessor as Superintendent of the Kew Observatory.

The apparatus is on the table. It consists, as is well known, of a circular coil which can rotate about a vertical axis. This generates an electromotive force in the coil, and the current produced is measured by the ratio of this electromotive force to the resistance. A magnet is hung at the centre of the coil, and the current is also measured by its deflections. Equating these two values for the current, we find an expression for the resistance in terms of quantities which can be measured. Let me draw your attention to the formula—

If n = number of turns of wire on the coil;
a = radius of the coil;
N = number of turns per second made by the rotating coil;
θ = deflection of the magnetic needle at the centre of the coil;

we have $R = 2 n^2 \pi^3 N a \cot \theta$.

This neglects the effect of the self-induction of the coil and other corrections which in the aggregate are considerable. Thus if we know n and a and observe N and θ we can find R; and R is determined, be it noted, in terms of a length a and N the number of complete rotations per second, which is the reciprocal of a time. R is given absolutely in terms of the units of length and time.

The experiments were repeated in 1864 by Maxwell, Fleeming Jenkin, and Hockin. Thus the absolute resistance of a certain coil was determined, ohm coils could be compared with this by known methods, and the British Association standards were made thus.

Table III gives the results of the 1864 experiments, and the comparison with those of 1863.

In constructing the standard coil, in consideration of the much greater range of velocities used in 1864, the 1864 mean value was allowed to have five times the weight of the mean value obtained in 1863.

For the purpose of comparing two coils of nearly equal resistance the Committee used a modification of the Wheatstone bridge, due to Jenkin and indicated in Fig. 1. The bridge, made, I believe, by Messrs. Elliott Brothers for the work, is before you. It was employed recently, with quite satisfactory results, by Mr. F. E. Smith at the National Physical Laboratory to compare two coils. By its aid the Committee compared the resistance of the copper wire of the spinning coil with that of a german-silver coil before and after each spin.

Meanwhile, Matthiessen and Hockin had been at work determining the material of which the British Association Standards were to be made, and as the result of numerous experiments an alloy of 66 per cent silver and 33 per cent platinum was selected. The reasons for this choice are given in an appendix to the fourth Report, 1866, together with an account of the means taken to compare the standards with the german-silver coils used in the absolute observation. A number of coils were made and distributed to public authorities and others. Some were sold; Dr. Faraday, on behalf of the Royal Institution, was the first purchaser. The unit coils of various materials, and also two mercury units, were prepared to be deposited at the Kew Observatory, and it is stated that "anyone possessing a copy of the British Association Unit may have it compared at any future time against one of these coils for a small payment."

Some of these coils are on the table. They were taken by Clerk Maxwell to Cambridge, and formed the basis of the work of Chrystal

TABLE III.

Time of 100 Revolutions, in Seconds.	Values found for Coil in terms of 10^7 for each Experiment.	Value of B.A. Unit in Terms of $10^7 \frac{\text{metre}}{\text{seconds}}$, as calculated from each Experiment.	Value from Mean of each Pair of Experiments.	Percentage Error from Mean Value.
17·54	4·7201	1·0121	0·9978	− 0·22
17·58	4·5914	0·9836		
77·62	4·8848	1·0468	1·0040	+ 0·40
76·17	4·4871	0·9613		
53·97	4·6607	0·9985	0·9992	− 0·08
54·53	4·6666	0·9998		
41·76	4·6279	0·9915	0·9925	− 0·75
41·79	4·6275	0·9936		
54·07	4·6496	0·9961	0·9924	− 0·76
53·78	4·6146	0·9886		
17·697	4·6108	0·9878	1·0007	+ 0·07
17·783	4·7313	1·0136		
17·81	4·6452	0·9952	1·0063	+ 0·63
17·78	4·7489	1·0174		
17·01	4·7567	1·0191	1·0043	+ 0·43
16·89	4·6187	0·9895		
21·35	4·6834	1·0034	1·0022	+ 0·22
21·38	4·6727	1·0011		
21·362	4·6526	0·9968	1·0040	+ 0·40
21·643	4·7134	1·0096		
11·247	4·8658	1·0424	0·9981	− 0·19
16·737	4·5305	0·9707		

Probable error of R (1864) = 0·1 per cent.
Probable error of R (1863) = 0·24 per cent.
Difference in two values 1864 and 1863 = 0·16 per cent.
Probable error of two experiments = 0·08 per cent.

and Saunder, Fleming, Rayleigh and Schuster, and myself at the Cavendish Laboratory. For the past thirty years they have been in my charge. In 1900 they came at last to the place for which they were originally intended—the Kew Observatory, the first home of the National Physical Laboratory—and since that time have been one of the treasured objects of Mr. F. E. Smith's care. They are, I think, the oldest set of accurate electrical standards now in existence, the type and forerunner of many others. Contrast the unity which they have brought with the confusion of 1860. May we not say: "These be thy gods, O Israel, which have brought thee out of the land of Egypt and out of the house of bondage."

During their long history they have been intercompared many times, and the results afford interesting evidence as to the permanence of the materials of which they are made. Table IV gives the results of Matthiessen and Hockin's work. The main intercomparisons at later dates were made by Messrs. Chrystal and Saunder in 1876, Dr. Fleming in 1878–81, myself in 1888, and Mr. F. E. Smith in 1908. A careful discussion of the results leads to the conclusion that with the exception of the two platinum coils known as D and E, Nos. 35 and 36 of Hockin's Table, all the others have changed. Table V gives the results obtained on this assumption. It includes seven of the original coils and the two other platinum-silver coils F and Flat. In Table VI the values of the coils, expressed in terms of the resistance of mercury, are given for two dates separated by a period of 27 years. This leads to the same result as to the permanence of the platinum coils.

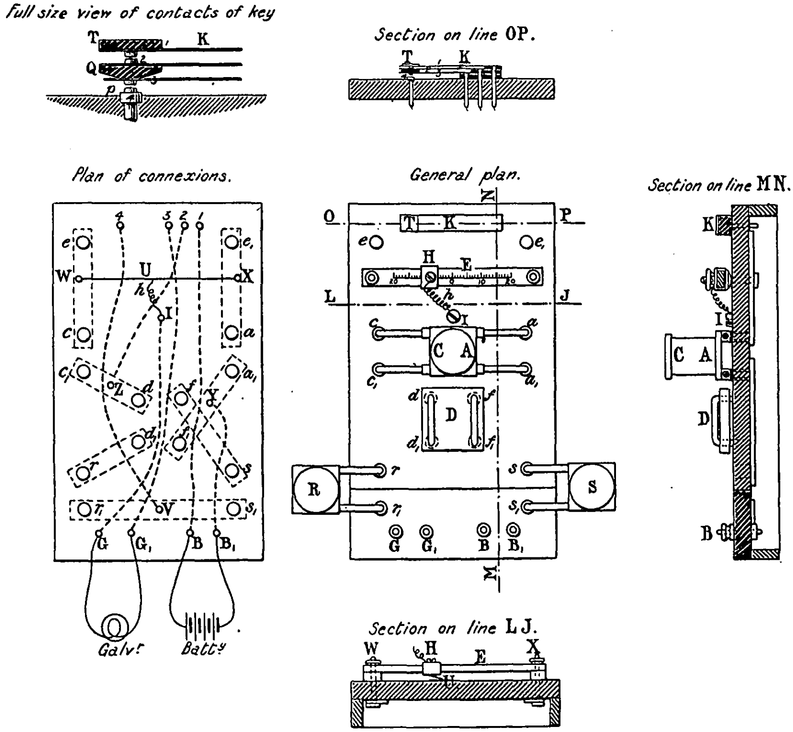

FIG. 1.—Fleeming Jenkin Resistance Bridge.

TABLE IV.

Material of Coil.	No. of Coil.	Date of Observation.	Temperatures at which coil has a resistance $= 10^7 \frac{m}{s}$.	Observer.
			°C.	
Platinum-iridium alloy	2	4th January, 1865	15·5	C.H.
		6th June, 1865	16·0	A.M.
		10th Feb., 1867	16·0	C.H.
Platinum-iridium alloy	3	4th January, 1865	15·3	C.H.
		6th June, 1865	15·8	A.M.
		10th Feb., 1867	15·8	C.H.
Gold-silver alloy ...	10	5th January, 1865	15·6	A.M.
		10th Feb., 1867	15·6	C.H.
Gold-silver alloy ...	58	10th April, 1865	15·3	A.M.
		6th June, 1865	15·3	A.M.
		10th Feb., 1867	15·3	C.H.
Platinum	35	7th January, 1865	15·7	C.H.
		18th August, 1866	15·7	A.M.
		10th Feb., 1867	15·7	C.H.
Platinum	36	7th January, 1865	15·5	C.H.
		18th August, 1866	15·5	A.M.
		10th Feb., 1867	15·7	C.H.
Platinum-silver alloy	43	15th Feb., 1865	15·2	C.H.
		9th March, 1865	15·2	A.M.
		10th Feb., 1867	15·2	C.H.
Mercury	I.	2nd Feb., 1865	16·0	A.M.
		18th July, 1866	16·0	A.M.
		11th Feb., 1867	16·7	C.H.
Mercury	II.	3rd Feb., 1865	14·8	A.M.
		18th August, 1866	14·8	A.M.
		11th Feb., 1867	14·8	C.H.
Mercury	III.	11th Feb., 1867	17·9	C.H.

TABLE V.

Resistances at 16·0° *C. in terms of the original B.A Unit* (1867).

(*Values obtained through the two Platinum Coils D, E.*)

Coil.	Material.	1867.	1876.	1879–81.	1888.	1908.	Maximum Difference.
A	Pt Ir	1·00000	1·00077	1·00056	1·00147	1·00122	147 × -10^5 B.A Unit
B	Pt Ir	1·00029	1·00121	1·00080	1·00104	1·00098	92 ,,
C	Au Ag	1·00050	1·00141	1·00101	1·00146	1·00173	123 ,,
D	Pt	1·00092	1·00092	1·00092	1·00092	1·00092	0 ,,
E	Pt	1·00152	1·00152	1·00152	1·00152	1·00152	0 ,,
F	Pt Ag	—	—	1·00016	1·00072	1·00160	144 ,,
G	Pt Ag	1·00022	1·00030	0·99982	1·00025	1·00175	193 ,,
H	Pt Ag	1·00020	—	—	1·00042	1·00044	24 ,,
Flat	Pt Ag	—	—	1·00079	1·00120	1·00125	46 ,,

But the history of the British Association coils is perhaps a digression: we are dealing with absolute units.

The original Committee was dissolved at its own request in 1870. During the next ten years further measurements of absolute resistance were made, notably by Kohlrausch and Rowland, and these seemed to show that the Committee's determination was some 1 per cent too low. The experiments of Joule, to be referred to later, led to the same result, and a similar conclusion may be deduced from Matthiessen's determination of the resistance of mercury. He states that the resistance of a metre-gramme of mercury is 13·06 B.A. units, while we now know that this quantity is approximately 12·79 ohms. Thus 1 B.A. unit = 0·979 ohm, or the B.A. unit is some 2 per cent less than its nominal value.

TABLE VI.

Giving the Values at 16·0° C. of certain Coils in cm. of Mercury in 1881, 1888, and 1908, obtained from comparisons with Mercury Standards.

Coil.	1881. Values deduced from Lord Rayleigh's determination of the specific resistance of mercury. F and Flat were used; for relative values of coils see Table V.	1888. Values at time of Dr. Glazebrook's determination. F, G, and Flat were used; for relative values of coils see Table V.	1908. Values directly determined through N.P.L. mercury standards of resistance.	Maximum Difference.
	Cm.	Cm.	Cm.	Cm.
A	104·847	104·946	104·918	0·071
B	104·872	104·901	104·893	0·029
C	104·894	104·945	104·972	0·078
D	104·885	104·888	104·887	0·003
E	104·948	104·951	104·950	0·003
F	104·805	104·843	104·959	0·154
G	104·769	104·807	104·974	0·205
H	—	104·836	104·837	0·001
Flat	104·871	104·898	104·922	0·051

Accordingly, on the motion of Professor Ayrton, the Committee was reappointed in 1880, and a series of redeterminations took place both in England and abroad. An international congress, the first of its kind, was to be held in Paris in 1881; and that year at the Jubilee meeting of the Association the first report of the new Committee was presented, and much discussion took place as to proposals to be made at Paris. Lord Rayleigh, and Schuster, had already shown by observations with old British Association apparatus that the original result was wrong by 1·2 per cent, and Lord Rayleigh was at work with a new coil. The Congress met, with Mascart and Eric Gérard as secretaries.* Sir William took a prominent part in its discussions. He proposed

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* *Nature*, vol. 24, p. 512, 1881.

the substantial adoption of the absolute system of the British Association; and after speeches by Wiedemann and Helmholtz, who favoured a mercury unit of resistance, the matter was adjourned and referred to a Committee. During the interval a compromise was arranged by the efforts of Mascart and Mr. (now Lord Justice) Moulton, and it was agreed that the fundamental units for electrical measurements should be those of the C.G.S. system—the centimetre, the gramme, and the second, while the practical units should be the ohm (10^9 C.G.S. units) and the volt (10^8 C.G.S. units). The name ampere was given to the current produced by a volt in a wire of resistance 1 ohm, 10^{-1} C.G.S. units, and it was agreed (1) that the unit of resistance 1 ohm should be represented by a column of mercury 1 square millimetre in section at the freezing-point of water, and (2) that an International Commission should be charged with the duty of determining by new absolute measurements the length of this column. Sir William, says his biographer, was the life and soul of the conference, and it was due to him that the absolute C.G.S. system was thus adopted internationally.

The article in *Nature* describing the work and dealing with the production of mercury standards concludes: "The German authorities assert that accuracy to one part in two thousand can thus be secured."

A number of determinations followed, and the Paris Congress met again in the spring of 1884. Mascart presented a table giving all the results then known for the length of the mercury column; the mean was 106·02 centimetres; and the first resolution of the Conference was: "The legal ohm is the resistance of a column of mercury a square millimetre in section and 106 centimetres in length at the temperature of melting ice."

Thomson had been one of the English representatives along with Preece, Carey Foster, and others, and had wished for the adoption of a figure more nearly in accord with recent Cambridge work. To adopt the mean of all known results, differing, as they did, among themselves by over 2 per cent, was far from satisfactory, especially as Rowland was then at work on the question and his results were unpublished. Accordingly, the "legal ohm" was never formally adopted here. By 1890 the question of establishing legalized standards in England had become ripe for settlement, and the Board of Trade appointed a Committee on Standards for the Measurement of Electricity for Use in Trade. The Committee consisted of Mr. Courtenay Boyle, Major Cardew, Mr. Graves, Mr. Preece, Sir William Thomson, Lord Rayleigh, Dr. Hopkinson, Professor Aryton, Professor Carey Foster, and myself.

Table VII and the top portion of Table VIII show the values available to guide their decision; and as the result they adopted as the resistance of the British Association unit the value 0·9866 ohm, and 106·3 centimetres for the length of the mercury column having a resistance of 1 ohm at 0° C. From these it follows that the resistance of 1 ohm in British Association units is given by—

$$1 \text{ ohm} = 1{\cdot}01358 \text{ B.A. units,}$$

TABLE VII.

	Observer.	Date.	Method.	Value of B.A. units in Ohms.	Value of 100 cm. of Mercury in B.A. units.	Value of Ohm in cm. of Mercury.
1	Lord Rayleigh ...	1882	Rotating coil	0·98651	(0·95412)	106·31
2	Lord Rayleigh ...	1883	Lorenz method	0·98677	—	106·27
3	Mascart	1884	Induced current	0·98611	0·95374	106·33
4	Rowland	1887	Mean of several methods... ...	0·98644	0·95349	106·32
5	Kohlrausch ...	1887	Damping of magnets	0·98660	0·95338	106·32
6	Glazebrook ...	1882 and 1888	Induced currents	0·98665	0·95352	106·29
7	Wuilleumeier ...	1890	——	0·98686	0·95355	106·31
8	Duncan and Wilkes	1890	Lorenz method	0·98634	0·95341	106·34
9	Jones	1891	Lorenz method	—	—	106·31
			Mean	0·98653		106·31
10	Strecker	1885	An absolute determination of resistance was not made. The value 0·98656 has been used	—	0·95334	106·32
11	Hutchinson ...	1888		—	0·95352	106·30
12	Salvioni	1890		—	0·95332	106·33
12	Salvioni	—		—	0·95354	106·30
			Mean	... ...	0·95354	106·31
13	H. F. Weber ...	1884	Induced current	Absolute measurements compared with german-silver wire coils issued by Siemens or Strecker		105·37
14	H. F. Weber ...	—	Rotating coil			106·16
15	Roiti	1884	Mean effect of induced current			105·89
16	Himstedt	1885	——			105·98
17	Dorn	1889	Damping of a magnet			106·24
18	Wild	1883	Damping of a magnet			106·03
19	Lorenz	1885	Lorenz method			105·93

Part of the apparatus used in the English determinations is before you, and Fig. 2 gives a view of Lord Rayleigh's apparatus. In explanation of the error made by the original Committee it should be stated that Lord Rayleigh had shown that it almost certainly arose from the assumption of a wrong value for the correction due to the self-inductance of the coil.

With a view to securing international agreement, publication of the Report of the Board of Trade Committee was deferred to the autumn, and the resolutions were discussed by the British Association, at Edinburgh, in 1892. Helmholtz, at Thomson's invitation, came over for the meeting, while Lindeck and Kahle, Dr. Guillaume and Professor Carhart also attended; and with a slight alteration in the form of words defining the mercury column, they were agreed to with the full concurrence of all. Sir William, who had become Lord Kelvin early in the year, was present and gave his valuable help.

TABLE VIII.

Value of the Ohm expressed as the Resistance of a Column of Mercury.

Lord Rayleigh ...	1882	Rotating coil	106·31
Lord Rayleigh ...	1883	Lorenz	106·27
Mascart	1884	Induced current	106·33
Rowland	1887	Mean of several methods	106·32
Kohlrausch ...	1887	Damping of magnets	106·32
Glazebrook ...	1882	Induced currents	106·29
Glazebrook ...	1888		
Wuilleumier ...	1888	—	106·31
Jones	1891	Lorenz	106·31
Jones	1892	Lorenz	106·32
Ayrton and Jones ...	1897	Lorenz	106·27
Guillet	1899	Induced currents	106·21
Campbell	1912	Alternating currents	106·27
		Mean	106·29

Next year, 1893, the Board of Trade Committee drew up an amended report to agree verbally with the Edinburgh resolutions, and at the International Conference in Chicago, held in August, 1893, under the presidency of Helmholtz, definitions were accepted for the international units in accordance with the same, while in August, 1894, the English Order in Council defining new denominations of standards for use in electricity under the Weights and Measures Act was approved by the Queen in Council. Resistance coils which had been compared with the British Association standards at Cambridge were set up at the

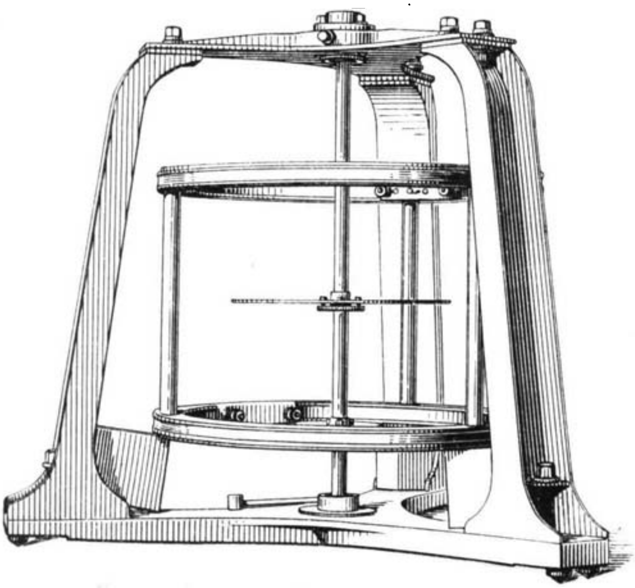


FIG. 2.—Lord Rayleigh's Lorenz Apparatus.

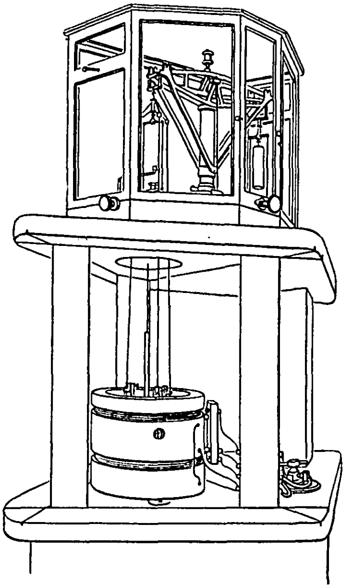


FIG. 3.—Board of Trade Current Balance.

Board of Trade Laboratory as the standard of electrical resistance, and a balance, calibrated by means of the silver voltameter, was constructed as a standard of current. This is shown in Fig. 3.

Leaving for the present the history of the unit of resistance for the last 18 or 20 years, let us turn to that of the other two units—those of current and electromotive force: it can be more brief. Only two of the three units are independent, and for a time it was not clear whether current or electromotive force should be chosen as the second. Weber indeed, in 1851, had selected these as the two fundamental units, defining them, however, in a manner that depended on the strength of the earth's magnetic field, which Gauss had shown in 1833 could be measured absolutely.

The relations between the various quantities occurring in electrical measurements are discussed in Appendix C to the second Report of the Committee by Clerk Maxwell and Fleeming Jenkin, and their statement should be carefully studied by every student. Electric currents, they point out, can be measured (1) by their action on a magnetic needle; (2) by their mutual action on each other; and (3) by their chemical effects. The first method is exemplified by the sine or tangent galvanometer, the second by the electrodynamometer devised by Weber (Fig. 4), or the current balance, and the third by the voltameter.

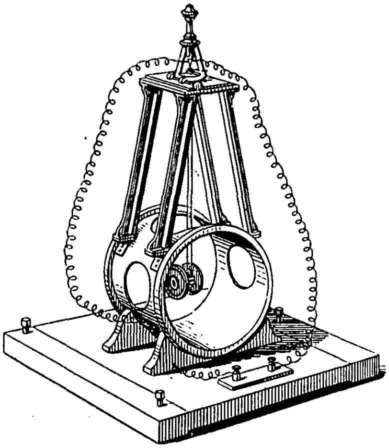


FIG. 4.—Weber's Electrodynamometer.

The first method is not suitable for absolute measurement because of the difficulty of determining H sufficiently accurately. The third involves the relation between the current and the amount of chemical action produced in the voltameter, and is therefore not an absolute measure; and we are thus left with the second—the electrodynamometer and the current balance. There are before you the earliest current balance and one of the earliest tangent galvanometers. They were used by Joule in his celebrated experiment.

This experiment was the well-known one of measuring the mechanical equivalent of heat by electrical means: it is described in the fifth Report of the Committee, Dundee, 1867, Appendix VI. Thomson had shown in 1851 how the results could be obtained. It was necessary, however, to know the resistance of a wire in absolute measure before they could be completed.

The result for the equivalent, assuming the British Association unit to be 10^9 C.G.S. units of resistance, was $42{\cdot}119 \times 10^6$ C.G.S. units, while the value found from the stirring of water was $41{\cdot}586 \times 10^6$ C.G.S. units. The agreement was thought to be very satisfactory by the Committee. They write, after stating that Joule thought the electrical method more accurate than the frictional:—

"Meanwhile the experiments already completed remove all fear of any serious error either in the number hitherto used as Joule's equivalent or in the British Association standard—a fear which hitherto, remembering the very discrepant results obtained by others, has been very naturally entertained even by the Sub-Committee from whose experiments the standard was constructed."

We know now that both Joule's figures were more nearly correct than the work of the Sub-Committee. The slight difference arose from the fact that the British Association unit is not exactly 10^9 C.G.S. units, and the ratio of the two figures just stated gives the value of the British Association units in ohms. This ratio is 0·9873, agreeing very closely with the figure 0·9866 which we have seen was accepted in 1893 as the value.

There is also on the table part of another electrodynamometer, that made for the Committee and referred to in the Reports for 1864 and 1865 and briefly described in that for 1869. Its coils were used by Lord Rayleigh in some experiments to be described later.

As to the volt, no direct means exist for determining it in absolute measure, at least if we exclude electrostatic measurements. Its measurement involves that of a current and a resistance, and the Committee in their second Report, 1863, suggests the use of a Daniell cell when the value of its E.M.F. is known in absolute units. The Daniell cell for this purpose has been replaced by the Clark cell (*Proceedings of the Royal Society of London*, vol. 20, p. 444, 1872) and, more lately, by the Weston cell. Up to 1881 the volt was retained in the second place as the second independent unit defined as 10^8 C.G.S. units of E.M.F., while the ampere was the current produced by a volt acting on an ohm. In 1884 this was altered; the ampere took the second place, defined as 10^{-1} C.G.S. units, while the volt was the E.M.F. required to maintain an ampere in a resistance of 1 ohm.

During the interval, current balances had been set up by Mascart and Rayleigh, who had measured the mass of silver deposited in one second by a current whose value was determined absolutely by the balance. This work was repeated by Kohlrausch and others, and it was recognized that a current of 1 ampere deposited per second from a solution containing silver about 0·001118 gramme of silver, provided certain conditions as to the voltameter and the solution were complied with. Knowing this figure, it became possible to measure currents or to standardize ammeters by the use of the silver voltameter. Again, using this figure to standardize a current and the known value of a suitable resistance, the E.M.F. of a cell can be measured; and it was found that the Clark cell set up with proper precautions had an E.M.F. of 1·434 volts at 15° C.

TABLE IX.

Electrochemical Equivalent of Silver.

		Mgm. per Sec.
1884	Rayleigh and Sidgwick	1·1179
1884	Kohlrausch	1·1183
1884	Mascart	1·1156
1890	Pellat and Potier	1·1192
1898	Kahle	1·1183
1898	Patterson and Guthe	1·1192
1903	Pellat and Leduc	1·1195
1904	Van Dijk and Kunst	1·1182
1906	Guthe	1·1182
1907	Smith, Mather, and Lowry	$1{\cdot}1182_7$
1908	Laporte and de la Gorce	$1{\cdot}1182_9$
1912	Rosa, Dorsey, and Miller	$1{\cdot}1180_4$

TABLE X.

E.M.F. of Clark Cell at 15° C.

		Volts.
1872	Clark	1·4378
1884	Rayleigh and Sidgwick	1·4345
1896	Kahle	1·4322
1899	Carhart and Guthe	1·4333
1905	Guthe	1·4330
1907	Ayrton, Mather, and Smith	1·4323

Indirect Determinations of E.M.F. of Clark Cell.

1884	Von Ettinghausen	$1{\cdot}433_5$
1885	Rayleigh	1·435
1892	Glazebrook and Skinner	1·434
1904	Trotter	$1{\cdot}432_9$

Lord Rayleigh's experiments at Cambridge, to which there are many references in Kelvin's life, were largely instrumental in establishing these results, and there are shown to-night parts of his current balance and some of the cells used by him; also cells constructed by

Principal Griffiths for his determination of Joule's equivalent. Fig. 5 gives a view of the balance. These various figures (given in the upper parts of Tables IX and X) then formed the basis of the English Order in Council of 23rd August, 1894, in which the ohm is said to have the value 10^9 in terms of the centimetre and the second of time, and to be represented by the resistance of a certain column of mercury 106·3 centimetres in length. The ampere has the value 10^{-1} in terms of the centimetre, gramme, and second, and is represented by a current depositing 0·001118 of a gramme of silver per second. The volt has the value 10^8 in terms of the centimetre, the gramme, and the second, and is represented by 0·6974 (1000/1434) of the electrical pressure between the poles of a Clark cell. The practical effect of this Order is the same as that of the resolutions of the Chicago Congress of the preceding year, which introduced the international ohm, ampere, and volt, and defined them thus:—

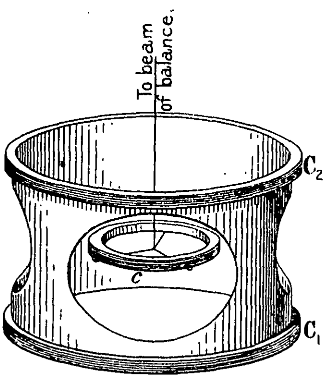


FIG. 5.—System of Lord Rayleigh's Current Balance.

The international ohm is said to be based upon the ohm equal to 10^9 C.G.S. units and to be represented by the resistance of a certain mercury column. The international ampere is 10^{-1} C.G.S. units and is represented sufficiently well for practical use by a current depositing 0·001118 gramme of silver per second; while the international volt is represented sufficiently well for practical purposes by 1000/1434 of the E.M.F. of a Clark cell at 15°C.

The difference in phraseology between the resolutions and the Order in Council should be noted. Moreover, according to the former, the international ohm is not 10^9 units, but is based upon this and is the resistance of 106·3 centimetres of mercury, while the international ampere and volt were defined as C.G.S. units and were to be represented by the current depositing a certain mass of silver and a certain fraction of the E.M.F. of a cell respectively.

So matters stood for some years. We pass now to more modern times. The National Physical Laboratory was opened at Teddington in 1902, and the resistance coils and other apparatus of the Committee came under the care of Mr. F. E. Smith. In 1897 Professor Viriamu Jones and Professor Ayrton described a new apparatus constructed for McGill University for determining the ohm by Lorenz's method, and in this apparatus the field coil consists of a single layer of wire wound in the helical groove on a marble cylinder. It followed from these results that the length of the column of mercury having a resistance of 1 ohm is 106·28 cm. The apparatus is shown in Fig. 6.

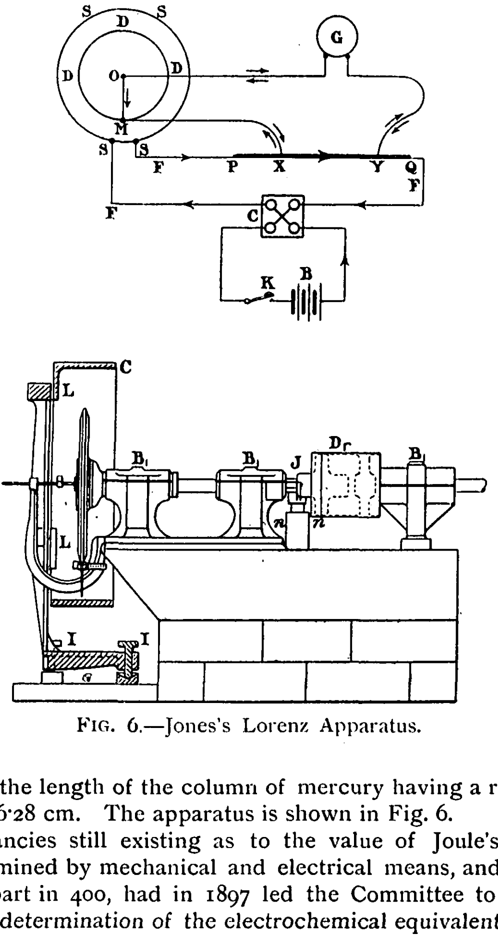


FIG. 6.—Jones's Lorenz Apparatus.

Discrepancies still existing as to the value of Joule's equivalent when determined by mechanical and electrical means, and amounting to about 1 part in 400, had in 1897 led the Committee to express the view that a determination of the electrochemical equivalent of silver—on which depended the value to be used for the E.M.F. of the cells employed in the electrical method—should be made; and next year, 1898, at the Bristol meeting, Ayrton and Jones described their design for an ampere balance of high accuracy. Jones's illness and death prevented the realization of this for some time. In 1903 it was arranged that a balance in accordance with their designs should be constructed at the Laboratory, and this was taken in hand. Meanwhile difficulties had been found with regard to the use of the Clark cell. An International Congress was held at St. Louis, in 1904, in connection with the Exhibition, at which attention was called to the fact that there were discrepancies between the laws relating to electrical units in the various countries represented, and urging the appointment of an International Commission to report on the matter. A conference was held at the Reichsanstalt in October, 1905, at which a resolution was passed in favour of holding an International Congress in London, and this took place in October, 1908. Among other things, the Berlin Conference recommended the adoption of a Weston standard cell in place of the Clark cell.

Meanwhile there appeared, in 1907, a series of papers giving the results of work by Ayrton, Mather, Smith, and Lowry, on the current balance, the silver voltameter, and the Weston cell; the results of these were of great value to the Congress, and an account of them follows later.

The Congress for the first time made a clear distinction between two sets of units—the ohm, the ampere, and the volt, and the international ohm, international ampere, and international volt. Let me spend a few moments in explaining the reason for this. The difference had been definitely recognized at Berlin and, to some extent, at Chicago, but the definitions there adopted were ambiguous. Thus the ohm is 10^9 C.G.S. units of resistance, and the international ohm is the resistance at 0° C. of a column of mercury of constant cross-section and having a mass of 14·4521 grammes and a length of 106·300 centimetres. The ampere is 10^{-1} C.G.S. units of current, while the international ampere is the current which when passed through a solution of nitrate of silver in water under certain specified conditions deposits silver at the rate of 0·00111800 of a gramme per second. The volt is 10^8 C.G.S. units of resistance, and the international volt is the electrical pressure which when steadily applied to a conductor having a resistance of 1 international ohm produces a current of 1 international ampere. The Congress also decided that the Weston normal cell might be conveniently employed as a standard of electrical pressure, having provisionally, at 20° C., an E.M.F. of 1·0184 international volt.

The reasons for the distinction may be briefly put. It had not been found possible to measure electrical quantities absolutely to the same accuracy as was obtained when comparing two resistances and two currents. Methods of comparing two resistances to an accuracy of some few parts in 100,000, or even of 1,000,000, were in use, and confusion was caused because in attempting to make a concrete standard to represent an ohm uncertainties of 1 or 2 in 10,000 were possible. It was necessary to have a standard more definite than any existing concrete representation of 10^9 C.G.S. units, and all that could be done was to construct some material standard of resistance having the necessary permanence and capable of being reproduced with the desired exactness. For the sake of securing the tremendous advantages of an absolute system, it was necessary that these concrete standards should approach as nearly as might be to the absolute units. The disadvantage of the continual change in standard required as each more accurate investigation approaches more nearly to the absolute value 10^9 C.G.S. units far outweighs the gain. We know that the ohm and the international ohm differ by a small quantity negligible for nearly every purpose: what that difference is, experiment will determine with ever-increasing accuracy; but the practical standard—the international ohm—remains fixed. The two zeros at the end of the figure 106·300 were added to make this clear. We often need to measure a resistance in terms of a standard to more than four figures; if the standard itself is only defined to four figures, such a comparison is unmeaning.

The change is of the same nature as that which has taken place in the centimetre and gramme. Originally the metre was one ten-millionth of the distance along a meridian arc between the pole and the equator; it is now the distance between two marks on a platinum-iridium bar at Paris. The kilogram was the mass of 1,000 cubic centimetres of water; it is now the mass of a certain lump of platinum.

Lengths could be compared with an accuracy far beyond that possible in measuring a meridional arc, and masses weighed against a standard mass with much higher exactitude than is reached in finding the mass of 1,000 cubic centimetres of water. So, too, with electrical quantities. Standards can now be set up in terms of the international units with an accuracy much in excess of that with which the ohm and ampere were known at the time of the London Congress, thanks in great measure to the co-operation between the National Standardizing Laboratories, secured by a Permanent Committee set up by the Congress. So far as England is concerned, the work of the Conference was confirmed by an Order in Council, dated January, 1910, and recognizing the three international units.

Lord Kelvin died a year before the London Conference was held and did not see the results of his long labours for the absolute system crowned by its international adoption. Its work was the natural outcome of deliberations in which for some forty years he took the leading part, and its success is a lasting memorial to the principles he laid down in the first Report of the Committee.

The Congress settled the definitions. There was more to be done, however, before it could be said that the standards which embodied those definitions in concrete form were uniform throughout the world, and this was left to Lord Rayleigh's Committee.

Meanwhile it remained also to determine as accurately as possible the differences between the ampere and the international ampere, and between the ohm and international ohm. Let us consider these briefly in order.

At the time of the Congress the researches with the Ayrton-Jones balance by Ayrton, Mather, Smith, and Lowry, had just been published. These were followed immediately by work in France by Janet and his colleagues, by Guillet and by Pellat. Professor Haga's work was published in 1910. A very elaborate series of experiments has just been published by Rosa, Dorsey, and Miller, of the Bureau of Standards, who write when describing the work at the National Physical Laboratory: "This work . . . marks the beginning of a new epoch in the history of the absolute measurement of electrical quantities."

Figs. 7 and 8 show the Ayrton-Jones current balance; Fig. 9 the balance of the Laboratoire Central d'Électricité; Fig. 10, Pellat's balance, and Fig. 11, the Bureau of Standards balance. The results with the Ayrton-Jones balance are given in Table XI.

TABLE XI.

Ayrton-Jones Current Balance. Value for E.M.F. of Weston normal cell, 1·01830 at 17° C.

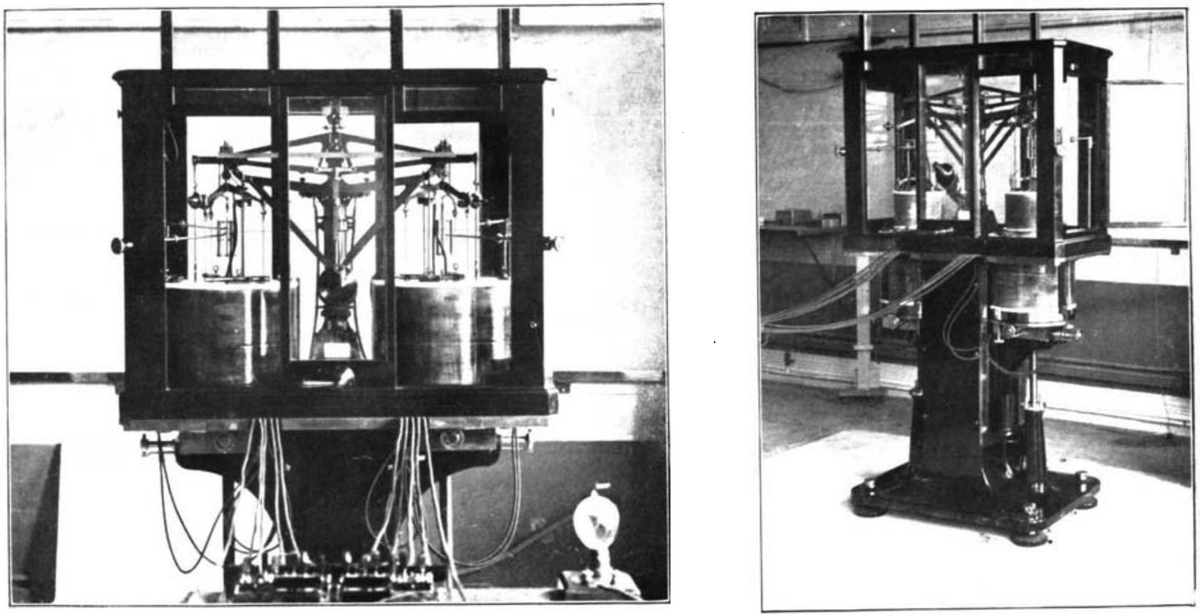
Of the 71 determinations made—

7	are within	1 part	in 1,000,000	of the mean.
14	"	2 parts	"	"
28	"	5 "	"	"
53	"	10 "	"	"
66	"	15 "	"	"
70	"	20 "	"	"

The difference between the Ayrton-Jones form of balance at the National Physical Laboratory and the Rayleigh form, or, perhaps, rather the Joule form adopted elsewhere, should be noted. In the National Physical Laboratory balance the actual dimensions of the coils can be measured with high accuracy. In the Rayleigh form, as Lord Rayleigh showed, the principal constant depends on the ratio of the mean diameters of the fixed and suspended coils, and can be determined by electrical means. Experiments are now in progress at the Reichsanstalt.

Summing up our knowledge at present, we may claim that the ampere deposits from a solution of nitrate of silver under definite conditions $0{\cdot}0011181_4$ gramme per second, and that, therefore, the international ampere is less than 10^{-1} units by $0{\cdot}01_3$ per cent.

As to the ohm, less has been done. Viriamu Jones at the time of his death was designing new apparatus for its determination by Lorenz's method, and the Drapers' Company had promised a generous grant towards its construction. In 1902 the Company intimated to the Committee of the National Physical Laboratory their wish to place £700 at the disposal of the Laboratory for the construction of the apparatus as a memorial to him. This was gratefully accepted, and the apparatus was designed by Mr. F. E. Smith; and with Sir Andrew Noble's generous help the machine was constructed at Elswick.



FIGS. 7 and 8.—Ayrton-Jones Current Balance at the National Physical Laboratory.

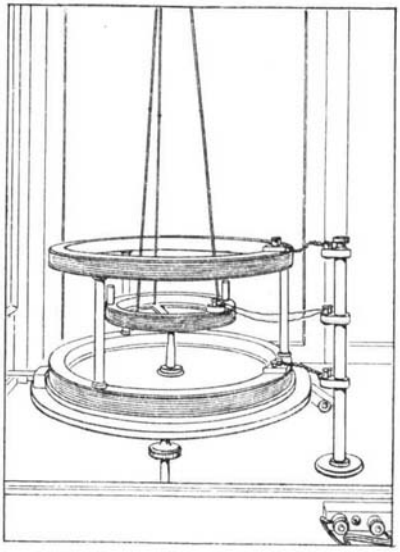
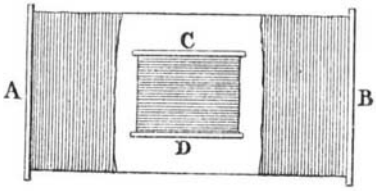


FIG. 9.—Current Balance (Suspended and Fixed Coils) of the Laboratoire Central d'Electricité.



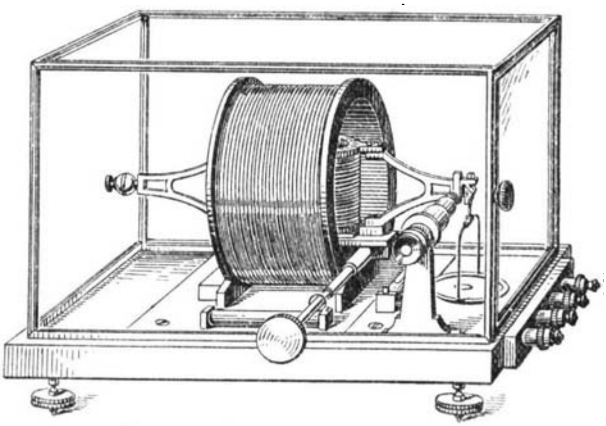


FIG. 10.—Pellat's Current Balance.

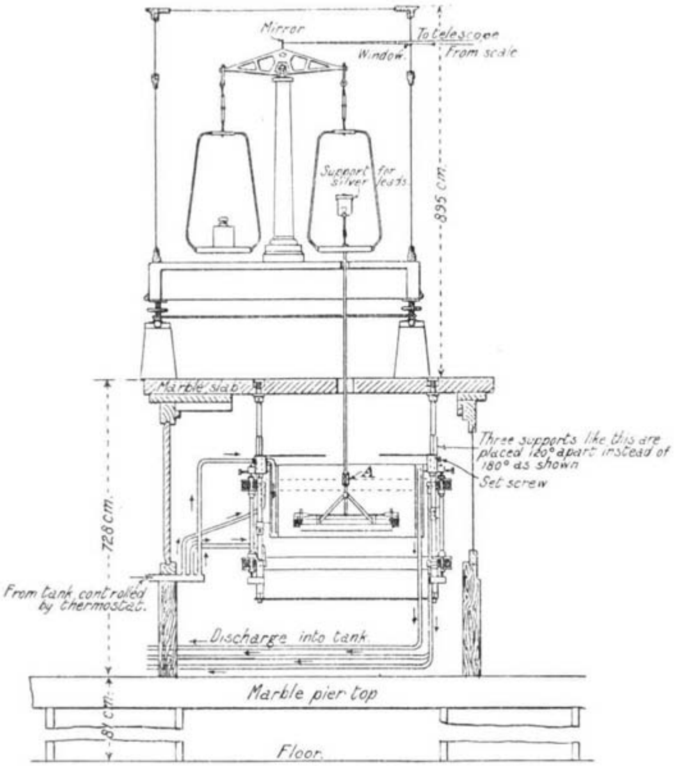


FIG. 11.—Bureau of Standards Current Balance.

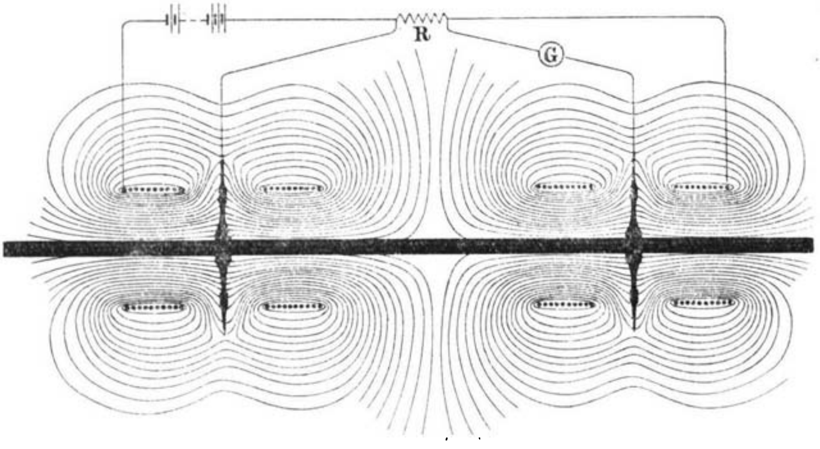
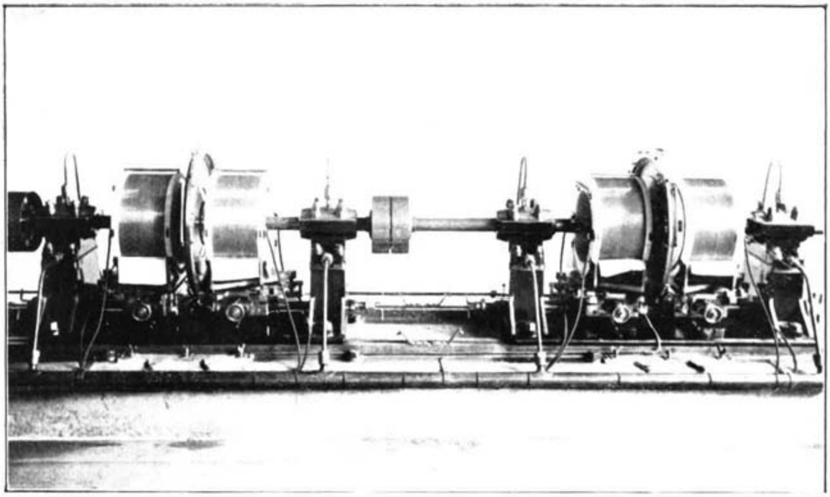
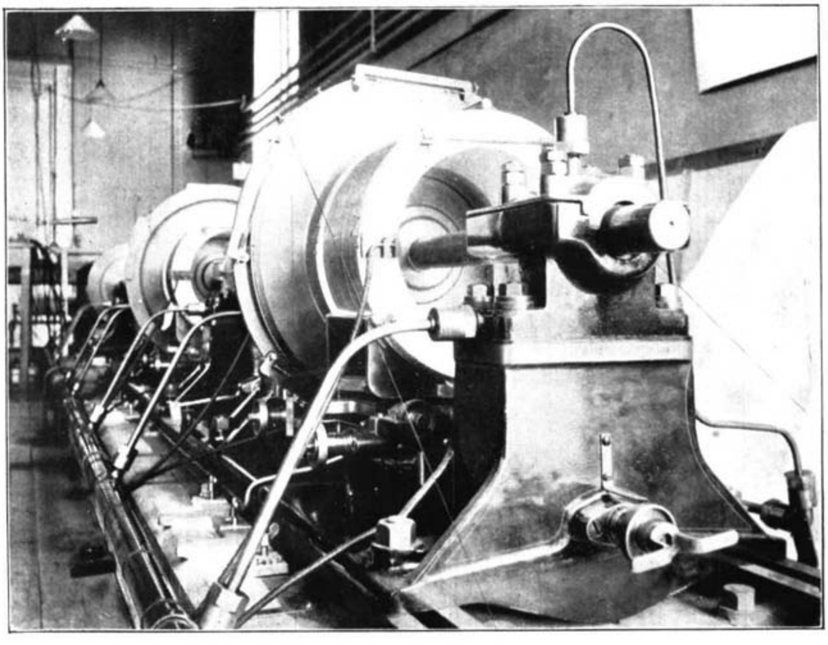


FIG. 12.—Diagram showing Magnetic Field of the Lorenz Apparatus at the National Physical Laboratory.





FIGS. 13 and 14.—Lorenz Apparatus at the National Physical Laboratory.

This machine differs from other apparatus of the kind in having two pairs of fixed coils and two rotating discs. This is shown diagrammatically in Fig. 12. The rubbing contacts, then, by which the E.M.F. generated in the rotating disc is picked off, are thus exactly alike, and the thermal E.M.F.'s generated at the contacts balance very approximately. With brushes rubbing on the disc and on the shaft respectively this is not the case. Again, the dimensions of the disc and coils are so chosen that in the position occupied by the edge of the disc the magnetizing field due to the coils is zero. Thus a slight error in the size of the disc produces a very small change in the number of lines of force which traverse it, and, hence, a very small error in the result. Again, the edge of each disc has been divided by Mr. Smith into ten insulated segments. The shaft is hollowed, and the corresponding segments on the two discs are connected by insulated wires passing through the hollow shaft. A certain E.M.F. (E, say) is produced when the discs rotate between each corresponding pair of segments. The brushes outside are so connected as to put these pressures in series. Thus the total E.M.F. is 10 E, and a resistance can be measured ten times as great as would be possible with the usual arrangement.

Figs. 13 and 14 show the machine.

Mr. Smith has just completed his first series of experiments, with the result that he finds that the length of the mercury column representing the ohm is less than 106·27 cm.

In 1912 Mr. Campbell made a determination by two interesting methods at the National Physical Laboratory. In one of these the coefficient of mutual induction of his standard inductance was compared by a modification of Carey Foster's method with the capacity of a standard condenser; the capacity of his condenser was then found by Maxwell's method in terms of a resistance, and thus the resistance was measured in terms of the mutual inductance and a frequency.

In the other method (Fig. 16) two nearly equal simple harmonic currents in quadrature are employed. One of these, $A \cos \omega t$, induces an electromotive force, $A \omega M \sin \omega t$, in the secondary of a mutual inductance. The other, $B \sin \omega t$, traverses a resistance, R, producing an E.M.F., $R B \sin \omega t$, between its terminals. The resistance R and the secondary of the inductance are in series with a vibration galvanometer tuned to the frequency of the current.

If the galvanometer is not deflected—

$$A \omega M = B . R, \text{ and thus } R = \frac{A}{B} \omega . M.$$

These observations of Mr. Campbell lead to the value 106·27 for the length of the mercury column representing 1 ohm, 10^9 C.G.S. units.

Since the Congress the Standardizing Laboratories of France, Germany, Great Britain, and the United States have co-operated as far as possible in securing identity of standards. This was greatly helped by a visit of representatives of the European Laboratories to Washington in 1910, rendered possible by the kindness of Dr. Stratton and the munificence of various electrical interests in the States. Tables XII–XVI show how fully success has attended these efforts. A number of mercury tubes have been constructed at the National Physical Laboratory lately, and Table XII gives their values in terms of the means of the whole series. The average difference is about 1 part in 100,000.

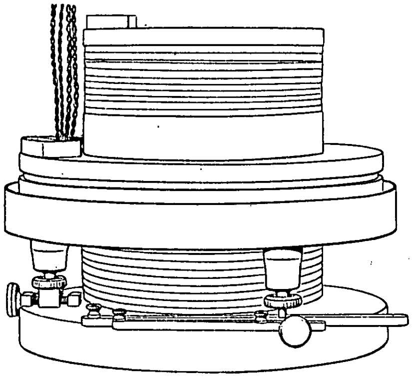


FIG. 15.—Campbell's Mutual Induction Standard.

In Table XIII we have the values of a series of coils compared with the standards in Washington, Paris, Berlin, and London. Tables XIV and XV give corresponding values for a number of Weston cells, while Table XVI shows the results of the series of combined experiments at Washington on the silver voltameter.

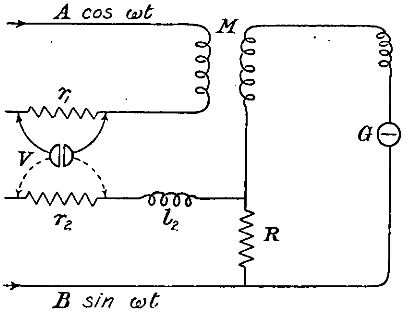


FIG. 16.

We may claim, I think, that, in spite of the forebodings of the technical men of 1862, the efforts of Kelvin and his colleagues have been successful; and, thanks to him, electricians possess a simple, accurate system of standards unequalled in any other science.

TABLE XII.

New Mercury Standards of Resistance.

No. of Tube.	Glass.	Length at 0° C. Mm.	Calibre Factor.	Mass of Mercury at 0° C.	Calculated Resistance, int. ohms.	Observed Resistance in Terms of Mean of all.	Diff. obs.—calc. 1 × 10—5.
2	Jena 16^{III}	1028·879	$1{\cdot}00010_1$	$13{\cdot}5540_1$	$0{\cdot}99986_6$	$0{\cdot}99986_0$	−0·6
6	" "	1058·125	$1{\cdot}00007_7$	$14{\cdot}3339_3$	$0{\cdot}99994_5$	$0{\cdot}99993_7$	−0·8
9	" 59^{III}	1000·756	$1{\cdot}00011_6$	$12{\cdot}8274_9$	$0{\cdot}99956_7$	$0{\cdot}99957_9$	+1·2
11	" 16^{III}	929·586	$1{\cdot}00018_1$	$11{\cdot}0679_7$	$0{\cdot}99965_6$	$0{\cdot}99967_0$	+1·4
27	" 59^{III}	812·187	$1{\cdot}00007_3$	$8{\cdot}4475_0$	$0{\cdot}99977_1$	$0{\cdot}99976_1$	−1·0
S	Verre dur	1188·249	$1{\cdot}00002_6$	$18{\cdot}0776_2$	$0{\cdot}99976_3$	$0{\cdot}99976_9$	+0·3
G	" "	1160·500	$1{\cdot}00012_8$	$17{\cdot}2438_9$	$0{\cdot}99983_8$	$0{\cdot}99985_5$	+1·7
1	Jena 16^{III}	1138·576	$1{\cdot}00002_9$	$16{\cdot}5965_0$	$0{\cdot}99986_1$	$0{\cdot}99985_8$	−0·3
130	" "	800·722	$1{\cdot}00007_3$	$8{\cdot}2197_8$	$0{\cdot}99967_3$	$0{\cdot}99968_0$	+0·7
137	" "	712·299	$1{\cdot}00000_8$	$6{\cdot}4993_4$	$0{\cdot}99948_0$	$0{\cdot}99946_0$	−2·0
5	Verre dur	1098·653	$1{\cdot}00007_1$	$15{\cdot}4645_7$	$0{\cdot}99916_5$	$0{\cdot}99917_1$	+0·6
11	" "	1024·146	$1{\cdot}00007_0$	$13{\cdot}4291_3$	$0{\cdot}99987_9$	$0{\cdot}99986_5$	−1·4
12	" "	1049·821	$1{\cdot}00010_0$	$14{\cdot}1116_4$	$0{\cdot}99984_5$	$0{\cdot}99985_6$	+1·1
13	" "	1061·576	$1{\cdot}00013_3$	$14{\cdot}4321_4$	$0{\cdot}99967_6$	$0{\cdot}99967_3$	−0·3

TABLE XIII.

International Comparisons of Resistances, 1912.

Coil No.	Bureau of Standards, June, 1912.	Laboratoire Central, Sept., 1912.	Physikalisch-Technische Reichsanstalt, Oct., 1912.	National Physical Laboratory, Oct., 1912.	Laboratoire Central, Nov., 1912.	Max. Difference.
11	$1{\cdot}00004_9$	$1{\cdot}00004_3$	$1{\cdot}00003_7$	$1{\cdot}00003_7$	$1{\cdot}00004_3$	$0{\cdot}00001_2$
12	5_1	4_5	3_7	3_9	4_2	1_4
3939	10_0	9_4	9_1	9_3	9_4	0_9
3940	10_1	9_4	9_3	9_5	9_7	0_8
Means	$1{\cdot}00007_5$	$1{\cdot}00006_9$	$1{\cdot}00006_5$	$1{\cdot}00006_6$	$1{\cdot}00006_9$	$0{\cdot}00001_1$

TABLE XIV.

E.M.F. of the Weston Normal Cell at 20° C. in terms of the Ampere (10^{-1} C.G.S.), and the International Ohm.

1905	Guthe	1·0185 volts.
1906	Ayrton, Mather, and Smith	82 "
1908	Janet, Laporte, and Jouast	86 "
1908	Lippman and Guillet	82 "
1908	Pellat	84 "
1910	Haga and Boerema	82 "
1912	Rosa and Dorsey	82 "

E.M.F. at 20° C. in terms of the International Ampere and International Ohm.

1906	Ayrton, Mather, and Smith	1·0184 int. volts.
1908	Laporte and de la Gorce...	84 "
1909	Jaeger and v. Steinwehr	84 "
1910	International Committee at Washington	83 "

TABLE XV.

International Comparisons of Weston Cells which travelled between the Various Laboratories. Differences in Microvolts.

Stand. Cell No.	B.S. June and July, 1911.	N.P.L. Aug., 1911.	P.T.R. Sept. and Oct., 1911.	N.P.L. Oct., 1911.	L.C.E. Oct., 1911.	N.P.L. Nov. and Dec., 1911.	B.S. Jan., 1912.
262	− 6	—	− 70	—	− 80	−60	—
267	41	—	0	—	—	—	—
268	37	—	− 15	—	—	—	—
51	−58	—	− 70	—	− 30	—	—
32	−69	—	−115	—	−130	—	—
301	−24	− 5	− 30	—	− 15	—	−40
304	19	23	0	—	0	—	7
309	−36	−27	− 45	—	− 20	—	−56
310	0	− 4	− 25	—	− 10	—	−44
A1	−13	−12	− 15	—	− 10	—	−22
43	2	3	− 30	—	5	—	0
44	0	—	− 15	− 7	—	—	− 1
19	−27	—	− 45	−30	—	—	−28
22	−31	—	− 40	−29	—	—	−30
238	− 2	—	20	52	—	—	−10
350	−24	—	− 20	1	—	—	−24
352	−31	—	− 45	−30	—	—	−30
133	—	—	—	—	30	—	34
142	—	—	—	—	30	—	33
1·3	—	—	—	—	—	− 6	− 5
1·33	—	—	—	—	—	−16	−16
17	—	—	—	—	—	− 5	− 8

TABLE XVI.

Comparison of Voltameters.

(Four forms of Voltameters and four experimenters—American, French, German, and British.)

Date, 1910.	Number of Voltameters in Circuit.	Calculated E.M.F. of Weston Normal Cell at 20° C.	Difference from Mean. 1×10^{-5}.
April 14	4	1·01825	−6
,, 15	8	33	−2
,, 18	4	27	−4
,, 20	8	31	0
,, 22	4	29	−2
,, 26	8	37	+6
,, 28	4	32	+1
,, 30	5	34	+3
May 2	7	37	+6
,, 3	5	36	+5
,, 5	8	35	+4
,, 7	8	28	−3
,, 12	6	30	−1
,, 19	4	26	−5

Mean = 1·01831.

Mr. Siemens.

Mr. ALEXANDER SIEMENS: I am delighted to see such a large audience of young men here to-night to hear the history of those electrical units which they are using every day, and which have proved of the utmost value in the practical applications of electricity. Those units have enabled us to compare without difficulty results obtained in different countries, and they have ensured that everybody who is engaged in research measures accurately; and, of course, science is measurement. No doubt Lord Kelvin did more than anybody else to develop the ideas which Professor Weber first set forth when he described his absolute system of units; but I should also like to draw attention to the fact that it was Dr. Werner Siemens who first suggested that mercury was the best substance of which to make the units of resistance. In trying to measure the resistance of cables, he found that a unit was absolutely necessary, and so he introduced a mercury unit of one metre length and one square mm. in section.* Without any doubt the scientific determination of the units and their relation to each other has helped us very much indeed. The practical units of which Dr. Glazebrook has spoken were introduced purely for commercial purposes, because it is impossible repeatedly to alter such units with the progress of exactitude in measurements. Dr. Glazebrook

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* *Poggendorf's Annalen der Physik und Chemie*, vol. 110, p. 1, 1860; and *Report of the Thirtieth Meeting of the British Association for the Advancement of Science*, p. 32, 1860.