Standardization of the Ohm as a Unit of Electrical Resistance, 1861–1867

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This month's history article takes a look at how the British Association Committee on Electrical Standards built the first internationally recognized material resistance standard, the BA unit of Resistance.

The first working telegraphs were built by several individuals in the 1830s and they began to be adopted into practical use in the 1840s prior to the laying of the first undersea telegraphic cable across the English Channel, before attempting to cross the Atlantic Ocean. A string of subsequent failures on undersea cables led to an acceptance of a need to measure, accurately, the resistance of both the wire and insulation. Prior to 1860, there was no widely accepted system of electrical units or standards. This article gives an overview of the historical development of the Ohm as a unit. In Section I, we discuss the telegraphic communication. Section II considers electrical resistance, Section III reports on the work of the British Association (BA) Committee, and Sections IV and V discuss the recognition and subsequent developments.

I. TELEGRAPHIC COMMUNICATION

The IEEE 2019 Milestone plaque in Barcelona commemorates Francisco Salvà Campillo's (1751–1828) design in 1804 of an electro-chemical telegraph proposed combining the generation of an electric current using a voltaic pile with detection by water electrolysis "to convey information at a distance." The 2009 IEEE historical plaque commemorates Pavel Shilling's (1786–1837) St. Petersburg electrical telegraph work was undertaken between 1828 and 1837. Carl Fredrich Gauss (1777–1855) and Wilhelm Weber (1804–1891) constructed in 1833 one of the first practical electromagnetic telegraphs in Gottingen, Germany, which operated at a distance of above 1 km. William Cooke (1806–1879) and Charles Wheatstone (1802–1875) subsequently introduced, in 1837, their first commercial telegraph (see Fig. 1). Werner Siemens (1816–1892) is also credited with his early pointer telegraph design in 1847 and, in 1848, he built the first long-distance telegraph line, 500 km in length, from Berlin to Frankfurt. Some of these early electric telegraphic systems required multiple wires, prior to the development of Samuel Morse's single-wire system. They could be used with either overhead wire or cable transmissions and were sometimes associated with railway communication or signaling.

In 1850, the Submarine Telegraph Company laid the first undersea telegraphic cable across the English Channel. It was unsuccessful as it comprised a simple copper wire, insulated with gutta-percha, but lacking outer armoring [1]. The next year, a cable with armored core was laid [1], [2] to give protection from ships, anchors, and the like. By 1853, further cables linked Britain with Ireland, Belgium, and The Netherlands [1]. A string of failures on the cables laid during 1853–1854 led to more care being taken, both in testing the quality

Digital Object Identifier 10.1109/JPROC.2019.2945495

Fig. 1. ***Cook and Wheatstone electric telegraph, courtesy Wikipedia, https://en.wikipedia.org/wiki/Electrical_telegraph.***

Fig. 2. ***Thomson's cable galvanometer, courtesy Hunterian museum, University of Glasgow.***

(i.e., resistance) of the wire conductor, in assessing the gutta-percha insulation and in improving the localization of the inevitable faults, which occurred on the installed cables so as to effect speedy repairs.

The first attempt in laying a transatlantic telegraphic cable was made in 1857 but only 330 mi were laid before the cable snapped. In 1858, the Atlantic Telegraph Company finally succeeded in linking Ireland with Newfoundland [3], but the cable was only in operation for 1 month. Subsequent attempts in 1865 and 1866 used a more advanced cable design and produced the first successful transatlantic cable. William Thomson (1824–1907) sailed on the international cable-laying expeditions of 1857, 1858, 1865, and 1866, the latter ones recognized as a triumph, with the principals of the project being knighted by Queen Victoria in November 1866. Sir William Thomson, who was subsequently ennobled as Lord Kelvin in 1892, was the first individual to be invited to sit in the House of Lords, based on his scientific achievements. He served as the Professor of Natural Philosophy for over 50 years at the University of Glasgow. For these long-distance undersea cables, only a very small current was available at the receiver, which was often implemented with a galvanometer. Fig. 2 shows Thomson's galvanometer that was the more successful of the two detectors used by the Atlantic Telegraph Company on its 1858 transatlantic telegraphic cable.

To further exploit his inventions for signaling on long submarine cables, Thomson entered into a partnership with Cromwell Fleetwood Varley (1828–1883), the Chief Engineer of the Electric and International Telegraph Company. Varley was a member of the 1859 joint committee between the Board of Trade and the Atlantic Telegraphic Company, which advised the government on cable projects and investigated cable failures. The other partner was Fleeming Jenkin (1833–1885), an Engineer from Newall's Birkenhead cable factory, across the Mersey from Liverpool, who had been responsible in 1855 for fitting out the Greenock built Elba cable-laying ship. Varley was an astute businessman and the partnership that he formed with Thomson and Jenkin, to exploit their respective telegraphic inventions, yielded these individuals significant personal profits (e.g., the £2500 annual payments they shared from the Atlantic Telegraph Companies). Jenkin was, for several years, the engineer in charge of international cable laying operations (with more than 35 international patents), often sailing on the Elba, prior to his appointment in 1868 by Queen Victoria as the first Regius Professor of Engineering at The University of Edinburgh.

By the late 1860s, these telegraphic cables comprised three across the Atlantic, several across the English channel and Irish sea, and others spanning the Mediterranean ocean. These installations grew rapidly from these beginnings, in this era before radio communication, to satisfy the requirement for efficient rapid long-distance communication. Jenkin delivered the public Cantor lectures on Submarine Telegraphy to the Royal Society of Arts in 1866. By 1872, there were telegraphic cables to India, China, Australia, and Japan, and soon after that to South America and along the coast of Africa. Fig. 3 shows the state of the international cable deployments in 1922, for the Eastern Telegraph Company that was formed in 1872 from various cable companies connecting Great Britain with its colonies in India, the far east, Australia, and New Zealand.

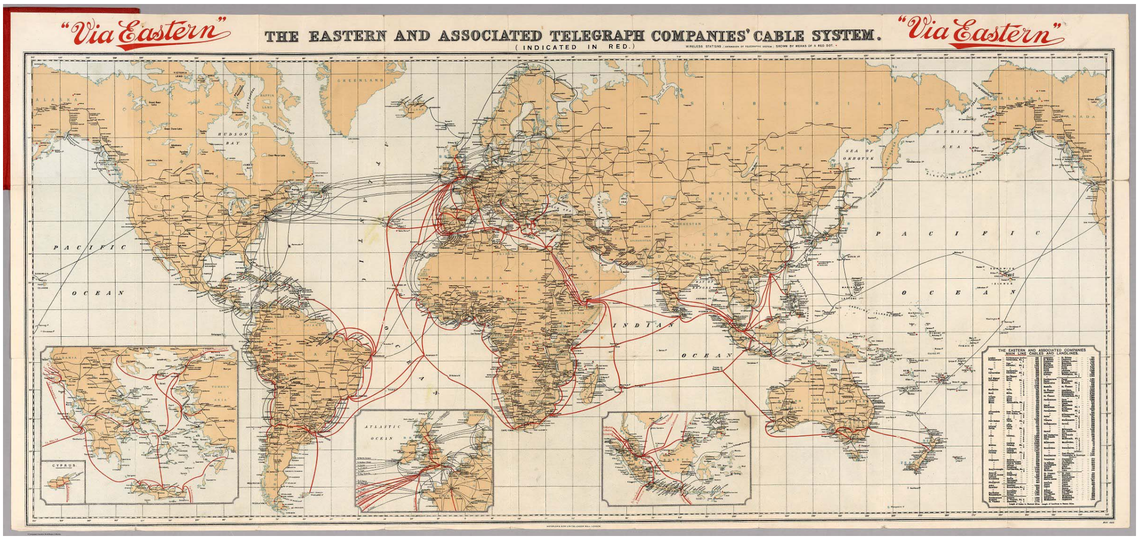


Fig. 3. *Cable map of 1922, from the David Rumsey collection, copyright by Cartography Associates under the creative commons license.*

II. ELECTRICAL RESISTANCE

Prior to the 1860s, there was no widely accepted system for measuring electrical units or standards. The rapid rise in electrotechnology described in Section II created a demand for a rational, coherent, consistent, and international system of units for electrical quantities. Telegraphers and other early users of electricity could only rely on specifying the weight or gauge of the conductor and measuring the chemical purity of the (normally copper) conductor, and thus they needed a practical standard unit of measurement for resistance. They often found that two apparently identical "pure" copper wires could differ by a factor of two in conductivity [4]. Reference [5] details the measurements on a set of four samples comprising 99.75% pure copper conductors and it comments on various impurities such as arsenic and antimony, which were discovered therein. Thomson's measurements in 1857 showed wide differences in the conductivity of different samples of copper intended for use in the cables so he persuaded the board to specify that only high-conductivity copper be used, particularly in the Atlantic cable of 1866. Resistance was often expressed, at this time, as a multiple of the resistance of a standard length of telegraph wire, and units were not readily interchangeable. Such electrical units did not belong to a system that was at all coherent with the units for energy, mass, length, and time, requiring conversion factors to be used in calculations relating energy or power to resistance [4].

In the 1850s, Michael Faraday (1791–1867) and William Thomson had shown that the capacitance of the cable caused "retardation" (or as it later came to be called, "distortion") of the transmitted current pulses. This effect had first been observed by Latimer Clark (1822–1898), who brought it to Faraday's attention in 1853. Thomson then established the theory of such signal transmission in 1854, demonstrating that retardation depended on the product of the total resistance and total capacitance of the cable; since both are proportional to the length, the total retardation increases with the square of the length of the cable. This contributed to a desire to know, with more accuracy, the precise resistance of the conductor. However, a much more important factor was the wish to ensure better quality control during manufacture to provide the ability to locate faults more accurately through measurements from the ends of the cable. In the 1850s and early 1860s, telegraphic-coded messages were typically limited to only one character every 4 s, but much higher rates of ∼20 words per minute were typical on the shorter submarine cables by the early 1870s.

Resistance coils, calibrated in feet of copper wire or similar small units, had been introduced earlier for laboratory use in the 1840s by Wheatstone, M. H. Jacobi, and others. Wheatstone had proposed adopting a foot of copper wire weighing 100 grains (6.5 g) in 1843, and Jacobi had sent copies [6] of a longer "etalon" to various physicists in 1848 [4], but neither of these coils was widely adopted as standards. These early attempts at establishing material standards were calibrated as miles of copper wire in the U.K., kilometers of iron wire in France, and miles of iron wire in Germany [4]. One hundred German units were manufactured by Siemens and Halske in Berlin in 1848, which were "equivalent to the resistance of a mile of copper wire, 1 line in diameter, at 20 °C" [7]. At this time, the resistance of a wire specimen was typically compared to that of one of the arbitrary chosen standards using a differential galvanometer (see Fig. 2) or a Wheatstone bridge [4].

An alternative to these arbitrary material standards of resistance had existed, at least on an article, in the "absolute" system based on units of force that Weber, building on Gauss's earlier magnetic work, had published in 1851 [4]. (Weber's system, which was based purely on forces, can be interpreted retrospectively in terms of the rate at which energy is dissipated in a resistor. It relies on the potential difference across a resistor when passing a unit current which dissipates one unit of work per second. In his electromagnetic system, the electromotive force was thus defined in terms of the potential difference between the ends of a wire of unit length when it was moved at right angles to a magnetic field of unit intensity, with unit velocity. Weber's system can thus be understood in terms of work and energy.) This "absolute" system required a very delicate measurement, with special apparatus, to determine the resistance of a given wire that was measured as units with a velocity [4], i.e., meters per second, but this proved later to be far too small a unit for practical use.

In 1860, Werner Siemens published an alternative suggestion for a reproducible resistance material artifact standard based on a spiral or folded column of pure mercury [8] of 1-mm^2 cross section, 1 m at 0 °C. His mercury-based unit, as shown in Fig. 4, was somewhat arbitrary in selecting a much larger value, which was no longer coherent with the earlier wire-related laboratory units, but, as it was about 1/20th of the resistance of a mile of ordinary telegraph wire [4], was a helpful step forward.

Charles Bright (1832–1888) and other engineers also favored the adoption of much larger material units, more in keeping with Siemens unit. Jenkin later noted [4], "the first effect of the commercial use of resistance was to turn the 'feet' of the laboratory into 'miles' of telegraph wire," and Bright's coils were indeed calibrated in equivalents of a mile of wire. The replication and refinement of such resistance coils in the 1850s and 1860s were thus crucial to initiating the spread of precision electrical measurement among engineers and physicists.

III. BRITISH ASSOCIATION

In 1861, the eminent cable engineers, Latimer Clark and Charles Bright, presented an article [9], [10] at the BA for the Advancement of Science meeting, suggesting that standards for electrical units be established. They suggested names for these units, which were "Ohma," "Farad," and "Volt" derived from the eminent philosophers Georg Ohm, Michael Faraday, and Alessandro Volta. However, because their unit of electromotive force (emf) was an arbitrary material one, their proposal did not cohere with the metric unit of work.

The BA had already appointed, on Thomson's suggestion, the BA Committee on Electrical Standards, with Jenkin acting as secretary. This committee was tasked to report upon and define Standards of Electrical Resistance [11], [12] and it produced essentially the system of Ohms, Amps, and Volts that we use today, with a far-reaching effect on virtually all later work on precision electrical measurement [11]. After the committee had initially met, it extended its remit to cover the connected system of units as proposed by Clark and Bright, prior to these individuals being appointed to join the committee.

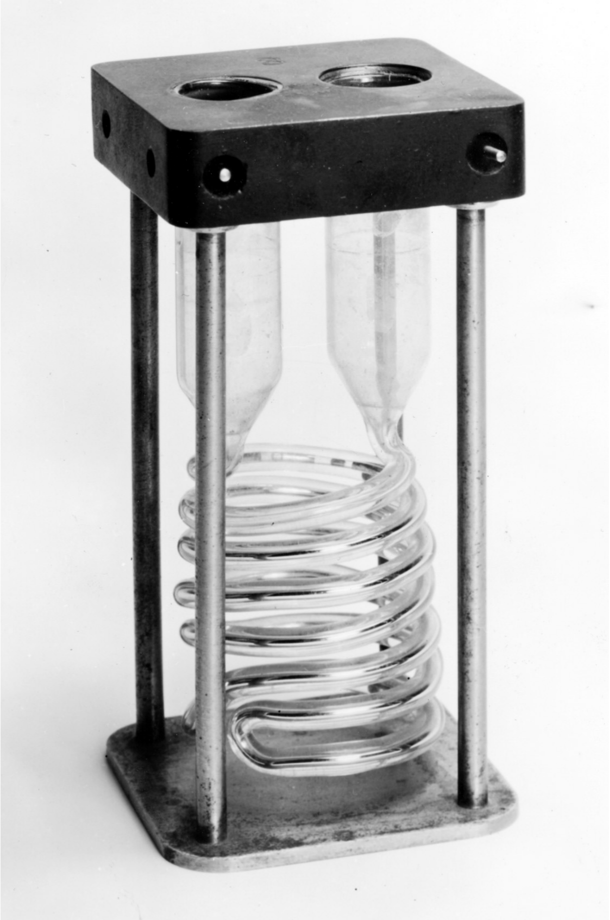


Fig. 4. ***Siemen's mercury column resistance unit, courtesy Siemens Historical Institute, Berlin.***

This committee initially included William Thomson; Charles Wheatstone; Augustus Matthiessen (1831–1870), a German-educated chemist and physicist; Alexander William Williamson (1824–1904), an English chemist; and William Hallowes Miller (1801–1880), a Welsh mineralogist and Cambridge professor. Later members up to 1870 included Charles Bright; Charles Hockin (1840–1882), an electrical physicist; Latimer Clark; James Prescott Joule (1818–1889), an English physicist and mathematician; James Clerk Maxwell (1831–1879), the celebrated Scottish scientist; Carl Wilhelm (later Sir William) Siemens (1823–1883), the younger brother of Werner Siemens and the head of the British branch of the Siemens enterprises; Balfour Stewart (1828–1887), a physicist and meteorologist; and Cromwell Varley. The committee thus comprised predominantly individuals whose scientific achievements had already been recognized by the award of Fellowships of the Royal Society (FRS) or the Royal Society of Edinburgh (FRSE). (It is interesting to note that Bright and Clark were the first to develop the prefixes Mega and Giga for 10^6 and 10^9, after recognizing that these prefixes were only needed for powers of 1000.)

The 1861 BA Committee's objectives were to devise a standard of resistance. A further objective, which devises a unified system of units based on the French metric system [11], [13] related to units of energy, was set by the committee itself, mainly at Thomson's behest, and this represented a significant extension of its original remit. The deciding factor in adopting metric rather than Imperial-based units seems to have been that a convenient decimal multiple of the metric absolute unit of resistance came out close to Siemens's mercury unit, which everyone agreed was of a convenient magnitude for cable work.

The BA committee thus aimed to establish a set of electrical measurement standards or units and deemed that they required four such quantities [6].

1) The unit of electromotive force or potential.
2) The unit of absolute electrical quantity or of static electricity.
3) The unit of electrical current, which should be formed by the combination of the unit of quantity with time. Such, for example, as the flow of the unit of electricity per second.
4) The unit of electrical resistance, which should be the same unit as that of current, viz., a wire that would conduct a unit of electricity in a second of time.

The apparent confusion between the units of current and resistance can be explained by their desire to create a set of material standards [6]. The BA committee readily identified this ambiguity and they clearly stated, in 1862, the need to differentiate between "units" and "standards" for resistance, i.e., a need to determine what would be the most convenient "unit" of resistance and what would be the best form and material for their "standard" representing that unit.

The committee recognized that their "unit" could be derived either from the quantity of energy dissipated in unit time when passing unit current, the so-called "absolute" unit, or by a material (wire or mercury) standard [6]. They dispensed with the absolute or physical units of Weber and adopted instead a set of material standards to readily enable the reproducible fabrication of standards. They were aiming for standards that provided permanency and they were anxious to relate these back to the "units" for everyday work [6]. The committee wished to ensure that standards "should be perfectly definite and should not be liable to require correction from time to time" [6].

The committee thus created the "BA unit of Resistance," an absolute unit based on the meter-gram-second (mgs) system. However, on working out the size of the mgs unit of resistance, they found it would be far too small for the needs of telegraph engineers. The BA Committee thus recommended a practical unit of resistance to be 10^7 times larger than the mgs absolute unit of resistance. The choice of the 10^7 multiplying factor to define the practical unit of resistance was somewhat arbitrary, but it was adopted because it gave the BA unit a value very close to that of the Siemens mercury unit. It also meant that 1 mi of the usual size of telegraph wire would have a resistance of approximately 10 Ohm in today's notation.

Fig. 5. ***BA Standard Resistor as first purchased by Michael Faraday in 1865, copyright London Science Museum, Science and Society Picture Library, rights reserved.***

As the selected BA unit of Resistance was just a few percent larger than Siemens's mercury unit [8], it was coherent with this definition. The committee thus attempted to make a material resistance standard that was as close as possible to 10^7 m/s and then define the resistance of that wire coil as their unit. They encountered several problems when performing absolute measurements of the required precision which meant it was late in 1863 before they could produce even a tentative resistance standard. In the third report of the committee (1864), the resistance unit is referred to as "BA unit" or, by Latimer Clark, as the "Ohmad" [11, p. 284]. Their early standard resistance coils consist of wire, insulated with white silk, wound round a hollow bobbin of brass, and mounted in annular copper cans [6], which were then filled with paraffin wax (see Fig. 5).

The BA Committee thus decided to adopt "one particular standard constructed of very permanent materials and laid up in a national repository" [11]. They developed small coils of specialist wire, 1–2 m long, to represent the early standards that had previously comprised miles of telegraph wire. They used several different alloys: platinum–silver, gold–silver, platinum–iridium, as well as pure platinum, for the wires within their standard coils. The coils were then prepared for the measurement of the BA unit of Resistance. As these were not absolute units, this name was adopted, as it ensured that any subsequent improvement in experimental measurement did not entail a change to the standard. After many painstaking measurements by Jenkin, Maxwell, Stewart, Matthiessen, and so on, the committee finally issued its official resistance standards in February 1865. Jenkin requested that these coils be deposited in a "public institution" [4], in a manner similar to the standard yard, in London. Siemens commented upon and questioned many times the absolute accuracy of the resistance measurements [7], [15].

In 1863 and 1864, Maxwell and Jenkin measured the resistance of two particular coils [6], which were later used to establish the 1-Ohm standard. By 1865, they claimed to have made ten resistors from precious metal alloys with copies from an alloy of platinum and silver [7], all adjusted as closely as possible. These particular materials were chosen for the grade of wire to ensure stability and minimize deterioration with age.

Jenkin then announced that copies of the standard resistance were now available, and that "A unit coil and box will be sent on receipt of the remittance of £2 10s" [16] or almost $200 in 2019 currency. These standard resistors, as shown in Fig. 5, were located first in the Kew Observatory, then at the Cavendish Laboratory in Cambridge, and so on, before transfer, in 1955, to the London Science Museum. Details of the coils within the brass case shown in Fig. 5 are given in both [6] and in from the 1865 fifth committee report [11]. The Science Museum confirms [17] that they cataloged in 1955 their set of nine original standard resistance coils, representing the "BA unit of Resistance," which had been constructed in 1864–1865 for the BA Committee on Electrical Standards. Seventeen of these standard coils were donated to the Directors of Public Telegraphs in nine continental states as well as India and Australia and a further 16 copies were sold.

It should be noted that Clark was reported in 1862 [6], somewhat before he joined the committee, to have commented that "the gentleman members are little connected with practical telegraphy," which was a surprising attack on Thomson and Jenkin given their extensive prior involvement in the design and installation of long-distance undersea telegraphic cables. However, later in the 1880s, Clark told Thomson that he had come to appreciate how wise the committee had been to adopt its own version of Weber's absolute system.

The actual instrument, proposed by Thomson, to define the BA unit of Resistance (see Fig. 6) suspended a small magnetic compass needle within a large spinning coil of the standard wire [19], [20]. Jenkin rotated the coil and Maxwell took the measurements as they led the experimental verification of the coil resistance along with Stewart and Charles Hockin, a later member of the committee. Spinning the current-carrying pair of series-connected coils at constant angular velocity in the earth's magnetic field produces an induced east–west magnetic field and causes the magnet to be deflected from its normal magnetic north–south orientation. The current in the spinning coils is inversely proportional to the coil resistance and, therefore, so will be the measured angle of deflection of the compass needle, at equilibrium [19]. These measurements, made at King's College on the Strand in London, were so sensitive that they encountered deflection oscillations arising from steamers close by on the river Thames. Matthiessen, aided by Hockin, subsequently made wire equivalents of the original coils, which involved making somewhat simpler measurements with a Wheatstone bridge or similar apparatus.

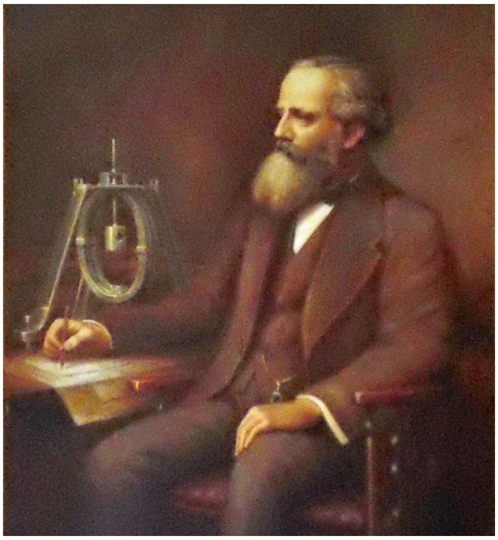
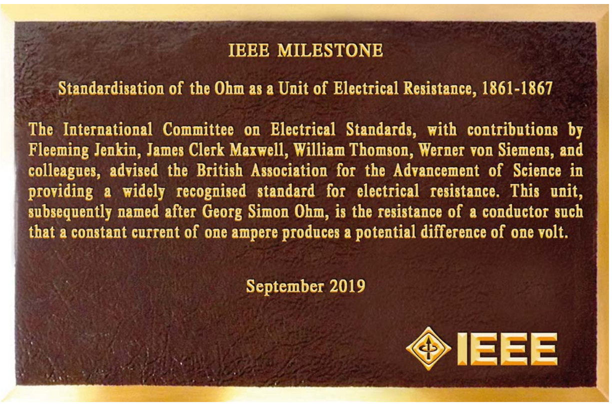


Fig. 6. ***Maxwell with the Thomson designed apparatus to measure the ohmic coil resistance, courtesy Institution of Engineering and Technology Archives, London.***

The text in [21] confirms that this revolving-coil apparatus, shown on the table in the Maxwell portrait in Fig. 6, was that designed by Thomson and the one used in 1863 to first determine the coil resistance. This portrait, painted in 1929 by R. H. Campbell, was based on a photograph of Maxwell in the possession of Sir Ambrose Fleming (1849–1945). Fleming was the English electrical engineer who invented the first thermionic valve and he designed the transmitter for the first transatlantic radio transmission. The painting in Fig. 6 was commissioned by the Institution of Electrical Engineers (IEE now IET) member, L. B. Atkinson, and donated immediately by him to the IEE in 1929. Atkinson's presentation speech [21] clearly describes the source material and subject matter. Reference [19] and Appendix D in the second report of 1863 in [11] provide further details on the experimental arrangement with the apparatus shown in the accompanying plates.

The BA Committee reports [13], [14] culminated in 1867 in the adoption of the unit that we now represent with the symbol Ω [18]. Following the progressive use of the commonly adopted term "ohm," in 1872, the name was changed from "BA unit of Resistance" to the "Ohm," naming it after the German physicist and mathematician Georg Simon Ohm (1789–1854). Using his own equipment design Ohm discovered, during studies on the electrochemical cell, the direct proportionality between the potential difference and voltage applied across a conductor and the resultant electric current. The fact that electric current is proportional to the potential difference was first discovered by Henry Cavendish (1731–1810) in 1781, but he never published these observations. Hence, they did not



IEEE MILESTONE

Standardisation of the Ohm as a Unit of Electrical Resistance, 1861-1867

The International Committee on Electrical Standards, with contributions by Fleeming Jenkin, James Clerk Maxwell, William Thomson, Werner von Siemens, and colleagues, advised the British Association for the Advancement of Science in providing a widely recognised standard for electrical resistance. This unit, subsequently named after Georg Simon Ohm, is the resistance of a conductor such that a constant current of one ampere produces a potential difference of one volt.

September 2019

IEEE

Fig. 7. ***IEEE Historical plaque on the standardization of the Ohm as a unit of electrical resistance, courtesy IEEE Historical Society.***

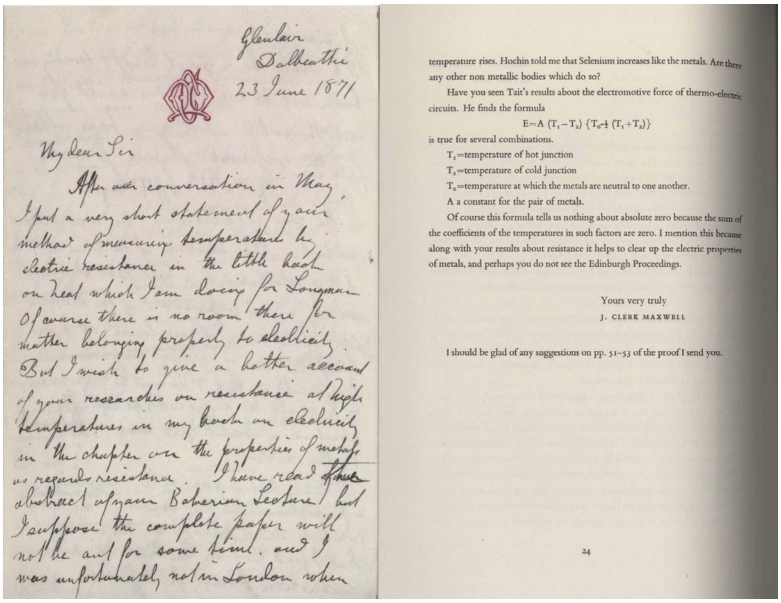
become generally known until Georg Ohm published his 1827 pamphlet [22]. The majority of Cavendish's electrical experiments remained unknown until they were collected and published in 1879 by Maxwell, who had established the Cavendish Laboratory in Cambridge in 1874, long after other scientists had been credited with the same results. Furthermore, in 1872–1873, Latimer Clark produced his zinc-mercury standard "Clark" cell, which provided an accurate reference of 1.4328 V at 15 °C, which facilitated more accurate measurements.

IV. RECOGNIZING THESE EARLY DEVELOPMENTS

These pioneering developments from 1861 to 1867 have now been recognized with an IEEE Milestone plaque, as shown in Fig. 7, located in the Hunterian Museum at the University of Glasgow alongside the many exhibits of William Thomson—Lord Kelvin's experimental apparatus. The plaque citation, which summarizes this achievement, reads as follows: "The International Committee on Electrical Standards, with contributions by Fleeming Jenkin, James Clerk Maxwell, William Thomson, Werner von Siemens, and colleagues, advised the BA for the Advancement of Science in providing a widely recognized standard for electrical resistance. This unit, subsequently named after Georg Simon Ohm, is the resistance of a conductor such that a constant current of one ampere produces a potential difference of one volt." A duplicate plaque will be installed in the James Clerk Maxwell Foundation museum in Edinburgh to recognize Maxwell's contributions.

V. SUBSEQUENT DEVELOPMENTS

These early measurements by Thomson, Maxwell, and so on, were accurate to within 1.3% of the Ohmic value used today [23]. The error is traceable back to the usage of an erroneous value for the inductance of the coil. With its main work completed, the BA Committee on Electrical Standards was disbanded in 1870. However, informal discussions on resistance continued (see Fig. 8). The Committee was next reconstituted in 1880 when it decided to take 10^7 m/s as the defined unit of resistance, and to adjust standards to get as close as possible to that, to correct for the 1.3% error. Reference [24] provides a commentary on the differences between German and British practices on precision and estimating probable error. The committee then continued its deliberations until 1913, in consultation with similar interested overseas bodies. After this time, U.K. standards activity transferred to the National Physical Laboratory.



Glenlair
Dalbeattie
23 June 1871

My dear Sir

After our conversation in May
I put a very short statement of your
method of measuring temperature by
electric resistance in the little book
on heat which I am doing for Longman
Of course there is no room there for
matter belonging properly to electricity
But I wish to give a better account
of your researches on resistance at high
temperatures in my book on electricity
in the chapter on the properties of metals
as regards resistance. I have read the
abstract of your Bakerian Lecture but
I suppose the complete paper will
not be out for some time. and I
was unfortunately not in London when

temperature rises. Hochin told me that Selenium increases like the metals. Are there any other non metallic bodies which do so?

Have you seen Tait's results about the electromotive force of thermo-electric circuits. He finds the formula

$$E=A\ (T_1-T_2)\ \{T_0-\tfrac{1}{2}\ (T_1+T_2)\}$$

is true for several combinations.

T_1=temperature of hot junction
T_2=temperature of cold junction
T_0=temperature at which the metals are neutral to one another.
A a constant for the pair of metals.

Of course this formula tells us nothing about absolute zero because the sum of the coefficients of the temperatures in such factors are zero. I mention this because along with your results about resistance it helps to clear up the electric properties of metals, and perhaps you do not see the Edinburgh Proceedings.

Yours very truly
J. CLERK MAXWELL

I should be glad of any suggestions on pp. 51–53 of the proof I send you.

24

Fig. 8. ***1871 letter from Maxwell to Siemens on the variation in resistance with temperature. Left: Maxwell's original first handwritten page, while transcribed on the right is Maxwell's conclusion, courtesy Institution of Engineering and Technology Archives, London.***

In 1881, a practical Ohmic unit used a mercury column, not dissimilar to that of Siemens. (Around 1881, Jenkin and Clark also proposed that the name Farad was adopted for the unit of capacitance [6].) In 1884, a legal Ohm standard was proposed as a compromise value between the BA unit of Resistance, the Siemens unit, and the above unit, but this was never adopted by any national legislation. This represented an intermediate stage of approximation to the international unit values we use today. The “international Ohm” was recommended later in 1893 [4] and became the basis for the legal definition of the Ohm in several countries, with further adoption in 1908 [25]. The interested reader is referred to [26], which gives this history in considerable detail.

By 1946, there were the “international Ohm” and the “absolute Ohm.” These were related by 1:1.00049 (this being the outcome of the “average” of measurements at independent government laboratories in six countries: Germany, United Kingdom, France, Japan, the United States, and the USSR) [27]. In 1948, the Ohm was redefined in absolute terms instead of as a material artifact standard.

Today, the international definition of resistance is based on the von Klitzing constant, whose value is approximately 25 812 Ω [28]. This is named after Klaus von Klitzing who received the Nobel Prize in 1985 for his work on the quantum Hall effect. The von Klitzing constant arises in measurements of the conductivity of semiconductors, which are subject to high magnetic fields when cooled to extremely low temperatures, approaching zero Kelvin. The advantage of this definition is that it does not require a physical resistor to represent it (see Figs. 4 and 5) but instead is based on a reliable and repeatable material property, which can be measured anywhere with suitable equipment. On May 20, 2019, the international system of base units (SI) was changed so that all seven base units including the unit of current, the Ampere, are now also defined based on constants of nature rather than physical devices or artifacts.

VI. CONCLUSION

The BA for the Advancement of Science appointed in 1861 the BA Committee on Electrical Standards and tasked it to report upon and define Standards for Electrical Resistance. The committee provided the development and enhancement of the earlier arbitrary material resistance standards, including those of Werner Siemens, to build the first internationally recognized material resistance standard, the BA unit of Resistance, subsequently called Ohm, after the celebrated physicist Georg Simon Ohm. Their 1865 units, which were accurate to within 1.3% of the value in use today, later became the International Units of 1893 and continued until they were superseded by the SI units in 1948. The Committee’s pioneering work initiated international collaboration to define the required standards for precision electrical measurement and assisted in defining the system of Volts, Amps, and Ohms that we use today. ■

Acknowledgments

The authors would like to thank the anonymous referee who has assisted them in clarifying and correcting a number of important aspects of this history. They would like to thank M. Baier of Siemens, Munich; W. Baier of Kaiserslautern University; E. Blocher of the Siemens Historical Institute, Berlin; A. Boyle, curator at the London Science Museum; J. Cable and A. O’Malley, archivists at The Institution of Engineering and Technology in London; L. Ogden from the British Science Association; N. Reeves, science curator at the Hunterian Museum Glasgow; and A. Savini of Pavia University, Italy; for their considerable assistance. They would also like to thank the late Lord Jenkin of Rodding, for sponsoring the original 2015 James Clerk Maxwell Foundation explanatory wall panel [29], which initiated our interest in this topic. The stimulus and continuing enthusiastic support of T. Davies and C. Turner were crucial in bringing to fruition the IEEE Milestone plaque installation at the Hunterian Museum to recognize these early significant scientific historical developments.

Acknowledgment of Sponsor

This article was sponsored by L. Dennis Shapiro. L. Dennis Shapiro is an IEEE Life Fellow and retired Chairman and past CEO of Lifeline Systems, Inc., now a part of Philips Electronics. He is a collector of historical manuscripts, including letters and documents signed by the early developers of electricity and radio communications. For information on supporting future Scanning the Past articles, please contact Stan Retif of the IEEE Foundation at s.retif@ieee.org.

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