THE DEVELOPMENT OF ELECTRICAL TECHNOLOGY IN THE 19th CENTURY:

1. The Electrochemical Cell and the Electromagnet

by W. James King

This paper—first in a series tracing the early history of electrical invention—deals with two devices basic to most of the later inventions in this field.

Starting with the early researches of Luigi Galvani and Alessandro Volta in the late 1700's, it highlights developments involving the electrochemical cell and the electromagnet during the period that culminated in the invention of various electric motors in the mid-19th century.

Among the devices described and illustrated are objects in the collections of the Smithsonian. They include the 1831 electromagnet of Joseph Henry, later to become first head of the Institution, and the U.S. Patent Office model of Thomas Davenport's electric motor, the first to be patented in America.

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MUCH of electrical technology depends upon an understanding of the properties of a coil of wire about an iron core. When an electric current is sent through a coil, the coil becomes an electromagnet that produces a mechanical force which may be turned on and off; moreover, this mechanical force may be controlled at a distance and in any arbitrary manner. On the other hand, an electric current is induced in the coil if a magnet is moved near it. Almost all electrical machinery with moving parts depends on these simple properties.

Static electricity had been known for some time before electromagnetism was discovered. However, it was not until the chemical cell was devised and made practical that electromagnets could be applied to invention. The first part of this article deals with the story of the chemical cell, together with some of its first commercial applications; the second part concerns electromagnets and how they were first applied to motors.

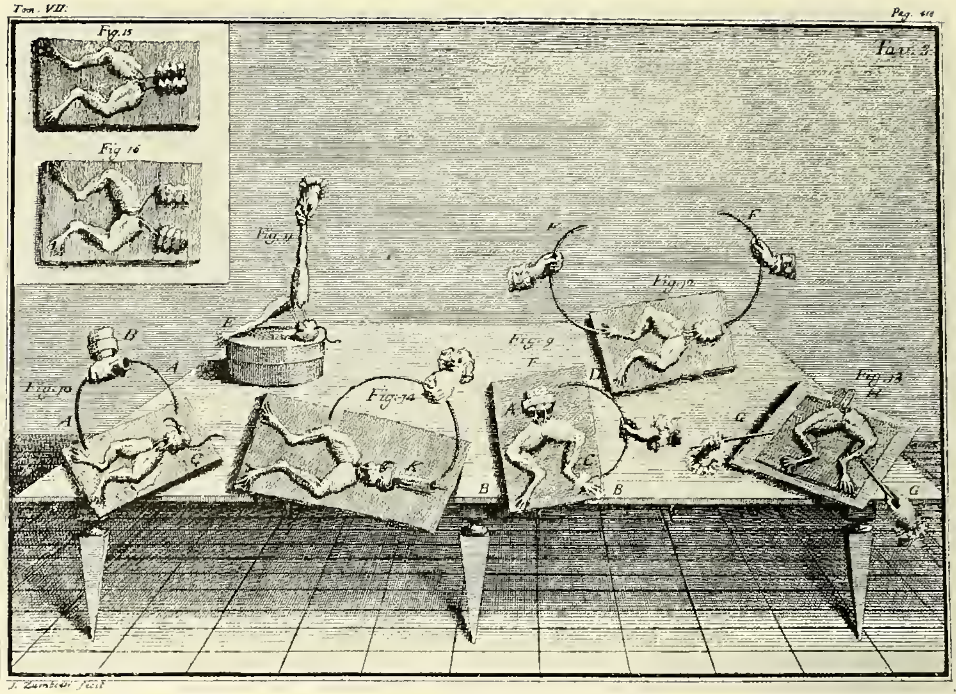

Figure 1.—Galvani's experiments in animal electricity. From Luigi Galvani, *De Viribus Electricitatis in Motu Musculari Commentarius*, Bologna, 1791, translated by Margaret Foley, Norwalk, Connecticut, 1953, pl. 3.

The Electrochemical Cell

Luigi Galvani, professor of anatomy at Bologna, was studying the relation between electricity and muscular tissue when he discovered that if the exposed nerve of a frog's leg were touched by metals under certain conditions, a contraction of the muscle would result (figs. 1, 2). This discovery led Galvani to explain muscular contractions in terms of an electrical nervous fluid being conducted, stored, and discharged.[1] Tissue, living or dead, was the receptacle of this fluid, and so could act as a kind of Leyden jar. Previous experience had shown that a Leyden jar could produce a spark only after "electrical fluid" had been condensed in it; however, an electrical effect could be detected in the tissue each time. Because of this, the suspicion arose that perhaps the electrical fluid might be some kind of life force.

Galvani's explanation was first elaborated [2] and then contested [3] by Alessandro Volta, who finally concluded that animal tissue was not necessary to produce the electrical effect and that all that was needed was two dissimilar metals separated by a poor conductor.[4] As a result of his research, Volta was able to design his famous voltaic pile (figs. 3, 4), which multiplied the effect of a single pair of dissimilar metals. The pile was formed by stacking pairs of metals separated by disks of paper moistened with salt water in the sequence: silver-paper-zinc-silver-paper-zinc, etc. These piles were found to increase their

[1] Luigi Galvani, *De Viribus Electricitatis in Motu Musculari Commentarius*, Bologna, 1791, translated by Margaret Foley, Burndy Library Publication No. 10, Norwalk, Connecticut, 1953.

[2] Alessandro Volta, "Account of Some Discoveries Made by Mr. Galvani, of Bologna; with Experiments and Observations on Them," *Philosophical Transactions of the Royal Society of London* (hereinafter referred to as *Philosophical Transactions*), 1793, vol. 83, pp. 10–44.

[3] Allesandro Volta, "Observations on Animal Electricity; Being the Substance of Two Letters from A. Volta to Professor Gren," *Philosophical Magazine*, 1799, vol. 4, pp. 59–68, 163–171, 306–312.

[4] Alessandro Volta, "On the Electricity Excited by the Mere Contact of Conducting Substances of Different Kinds," *Philosophical Magazine*, 1800, vol. 7, pp. 289–311.

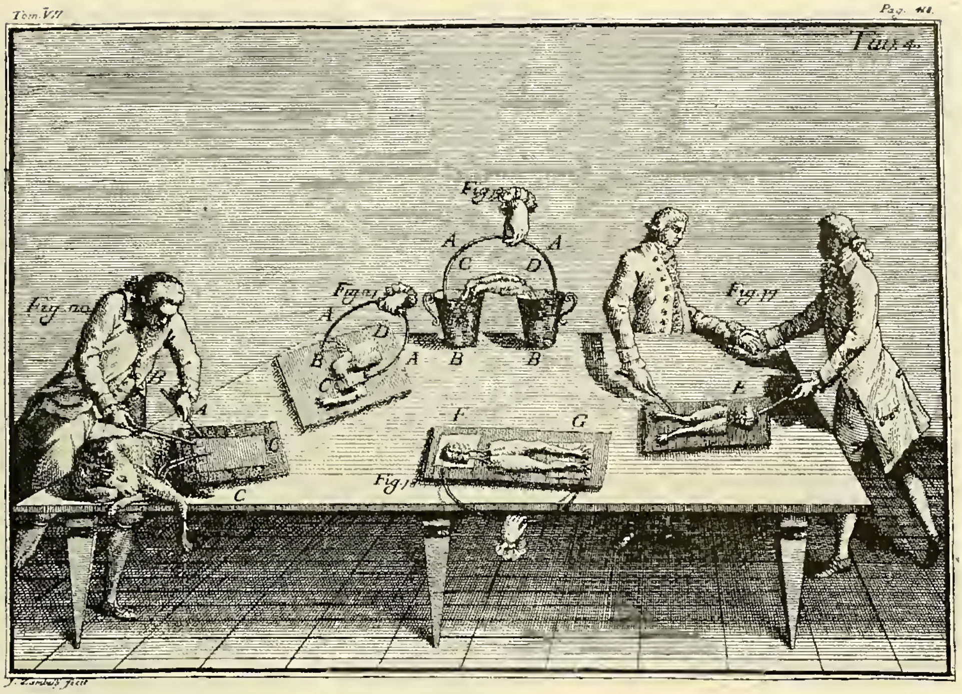

Figure 2.—Galvani's experiments in animal electricity. From Luigi Galvani, *De Viribus Electricitatis in Motu Musculari Commentarius*, Bologna, 1791, translated by Margaret Foley, Norwalk, Connecticut, 1953, pl. 4.

effects if more or larger plates were used; but, of course, the heavier the plates, the faster the paper dried out and the faster the pile ceased working. Such dehydration could be avoided by dividing the pile in half and connecting several piles together. Even so, the pile usually was effective for only a couple of days; then it had to be taken apart and cleaned before further use. Such devices (fig. 5) were in use during the first quarter of the 19th century. Volta devised a battery with a longer life in his "crown of cups." [5] This innovation consisted of a number of cups filled with a saline solution and with a pair of dissimilar metals in each cup. One metal electrode was joined to its opposite mate in the next cup, and so on, until a complete circuit was made. However, the "crown of cups" was much bulkier than the pile.

Volta's results were communicated in two well known letters to England, where they promptly stimulated further work. Even before the publication of the second letter, William Nicholson and Anthony Carlisle made a pile of 17 silver half-crowns and as many zinc disks.[6] This pile was not powerful enough for their electrochemical experiments, so they made another pile of 36 pairs, and then one of 100 pairs.[7]

Dissatisfied with the arrangement of the metals in a pile, William Cruickshanks devised his "trough" battery.[8] For this battery, 60 pairs of zinc and silver plates measuring about 1½ inches square were cemented with rosin and beeswax in a trough so that all the zinc plates faced one way and all the silver plates the other way. The cells formed by these metal partitions were "charged" by a dilute solution of ammonium chloride. Trough batteries (such as shown in figs. 6–8) might last several weeks instead of only a couple of days, but even so the

[5] *Ibid.*

[6] William Nicholson, "Account of the New Electrical or Galvanic Apparatus of Sig. Alex. Volta, and Experiments Performed with the Same," *Journal of Natural Philosophy, Chemistry, and the Arts* (hereinafter referred to as Nicholson's *Journal*), 1800, vol. 4, pp. 179–187.

[7] William Nicholson, Anthony Carlisle, William Cruickshanks, et al. "Experiments in Galvanic Electricity," *Philosophical Magazine*, 1800, vol. 7, pp. 337–347.

[8] William Cruickshanks, "Additional Remarks on Galvanic Electricity," Nicholson's *Journal*, 1801, vol. 4, pp. 254–264.

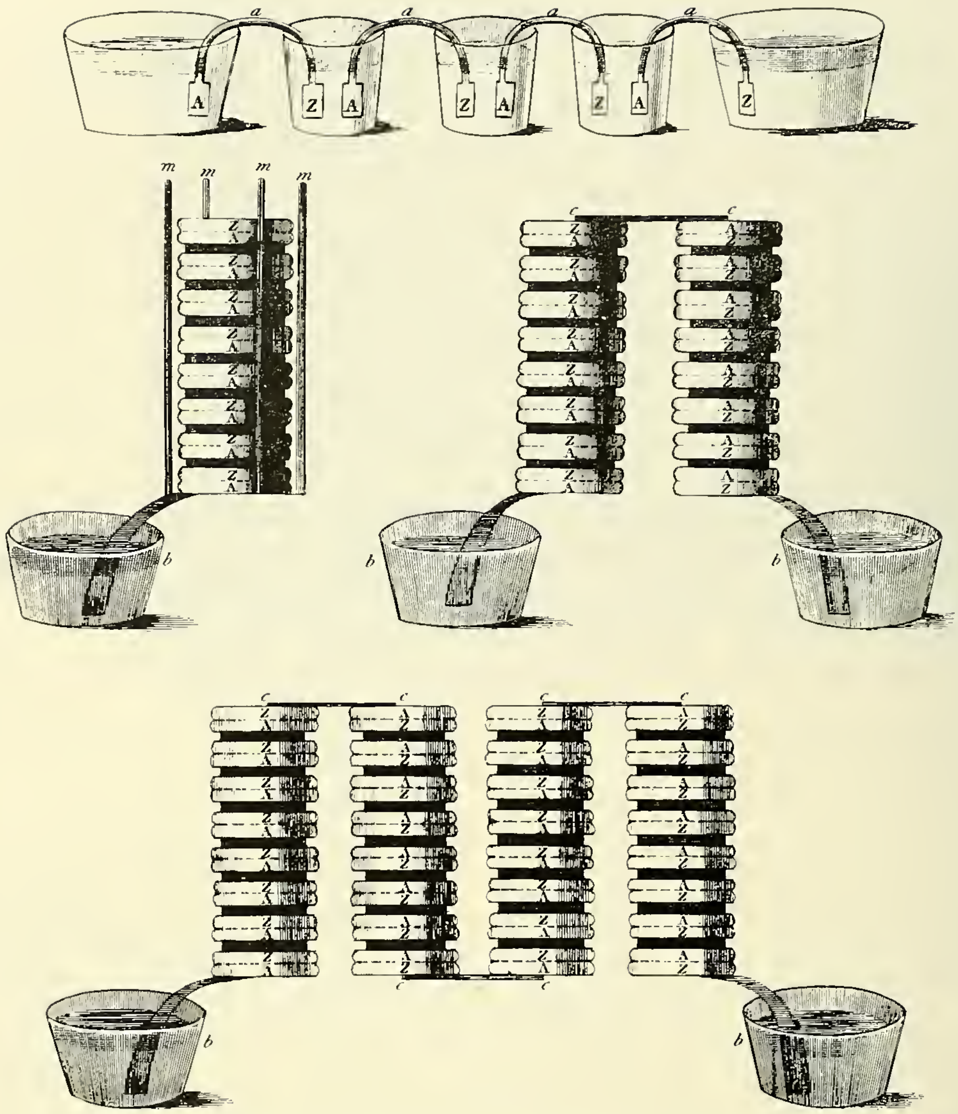

Figure 3.—Volta's "crown of cups" (at top) and his voltaic pile. From *Philosophical Transactions of the Royal Society of London*, 1800, vol. 90, plate opposite p. 430.

experimenter had "to hasten to complete his experiments before the power had materially declined." [9] Two years later William Pepys built two troughs (fig. 9) with 130 pairs of zinc and copper plates, each plate being 6 inches square.[10] Each trough was charged with dilute "nitrous acid." In 1807 Humphrey Davy used three such batteries to separate sodium and potassium from their compounds.[11] One battery had 24 pairs of copper and zinc plates 12 inches square;

[9] Benjamin Silliman, *First Principles of Chemistry*, Philadelphia, 1847, p. 115.

[10] William Cruickshanks, "Description of Mr. Pepys' Large Galvanic Apparatus," *Philosophical Magazine*, 1803, vol. 15, pp. 94–96.

[11] Humphrey Davy, "On Some New Phenomena of Chemical Changes Produced by Electricity, Particularly the Decomposition of the Fixed Alkalies, and the Exhibition of the New Substances which Constitute Their Bases; and on the General Nature of Alkaline Bodies," *Philosophical Transactions*, 1808, vol. 98, pp. 1–44.

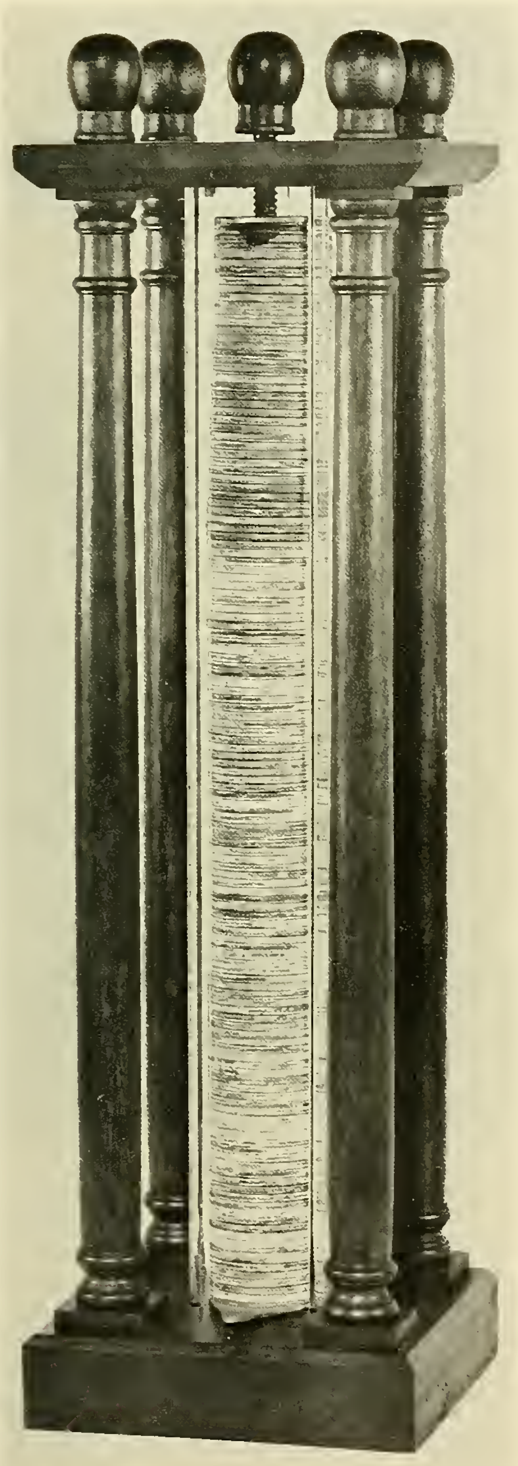

Figure 4.—Reproduction of voltaic pile of about 1810. The stand is about 4 feet high. (*USNM 315049; Smithsonian photo 47048–D.*)

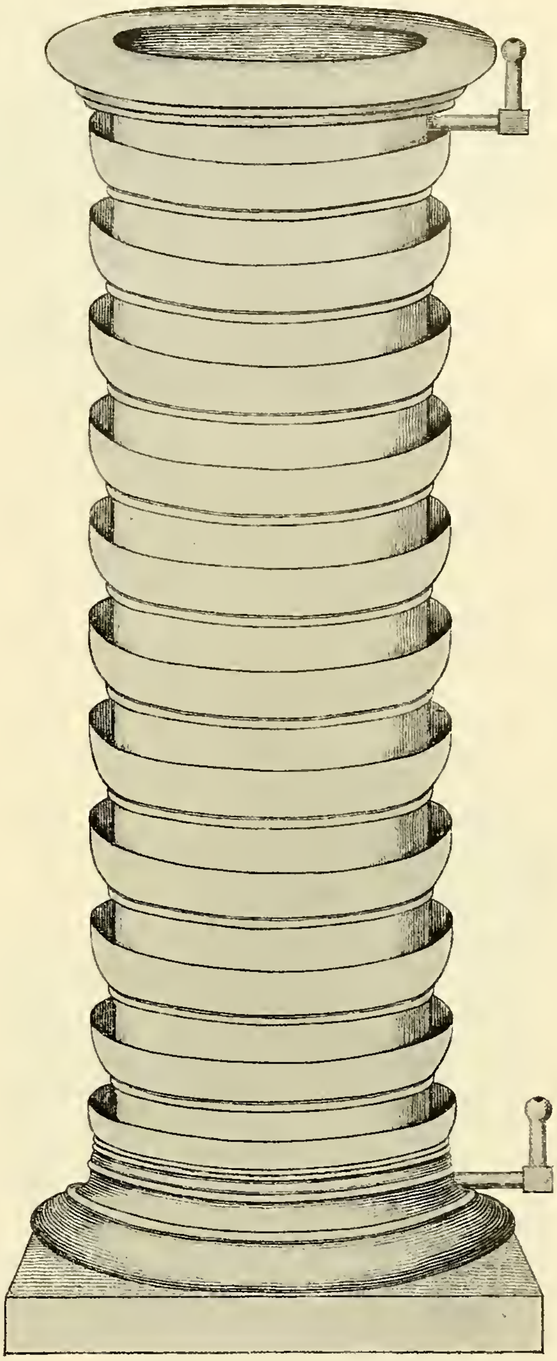

Figure 5.—Kemp's voltaic pile of 1828. From *Edinburgh New Philosophical Journal*, 1828, vol. 6, pl. 2, p. 71.

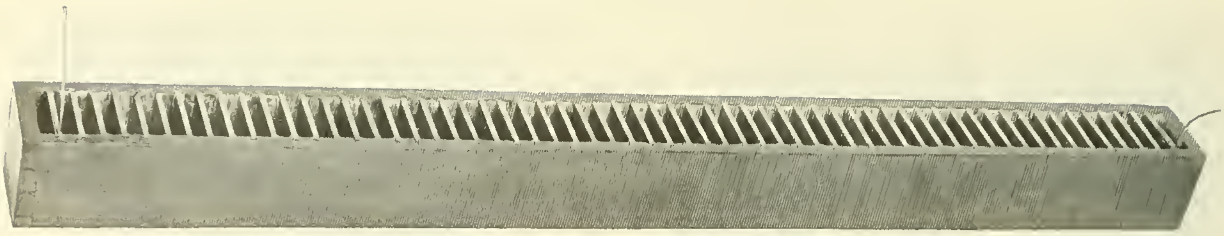

Figure 6.—Joseph Priestley's trough battery. (*USNM 315114; Smithsonian photo 47048–A.*)

one had 100 pairs of plates 6 inches square, and one had 150 pairs of plates 4 inches square. Alum and "nitrous acid" were used to charge the cells.

A trough battery could not be cleaned without some difficulty; and as long as the charge was in the battery it tended to dissolve any corrodible electrode. C. H. Wilkinson's "plunge" battery [12] avoided this dissolution by suspending the electrodes from a rod so that all the electrodes could be immersed at the same time and could be removed from the corrosive acid when not in use. In addition, both sides of an electrode were used, increasing the current output for a given amount of metal. A similar form of such a plunge battery was constructed by Pepys (fig. 10). J. G. Children made a plunge battery of 20 pairs of copper and zinc plates, each 4 feet high and 2 feet wide, with a "charging" fluid of dilute nitrous and sulfuric acid.[13] In the following year, the "Great Battery" [14] of the Royal Institution of Great Britain was constructed on a similar plan (fig. 11). In this battery there were 200 porcelain troughs, each of which constituted a plunge battery of 10 pairs of electrodes that were 4 inches square. With the use of this battery Davy isolated the alkaline earth metals.[15]

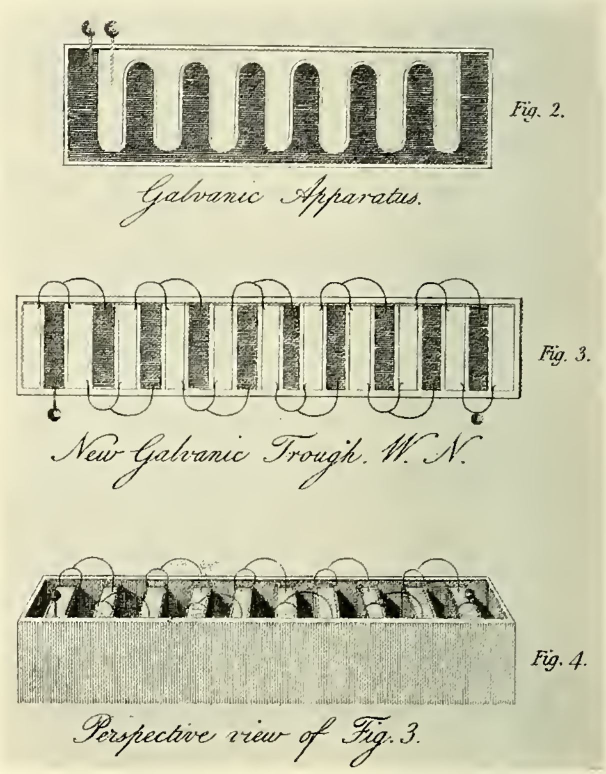

Figure 7.—Nicholson's trough battery. From Nicholson, ed., *A Journal of Natural Philosophy, Chemistry, and the Arts*, 1804, vol. 8, p. 64, pl. 3.

Volta's pile of n pairs of metals increased what he

[12] C. H. Wilkinson, "On the Means of Simplifying and Improving the Galvanic Apparatus," Nicholson's *Journal*, 1804, vol. 8, pp. 1–5; "Facts upon which Deductions Are Made to Show the Law of Galvanism in Burning the Metals, According to the Disposition of Equal Surfaces of Charged Metallic Plates," Nicholson's *Journal*, 1804, vol. 7, pp. 206–209; "Description of an Improved Galvanic Trough," *Philosophical Magazine*, 1807, vol. 29, pp. 243–244.

[13] John G. Children, "An Account of Some Experiments, Performed with a View to Ascertain the Most Advantageous Method of Constructing a Voltaic Apparatus, for the Purpose of Chemical Research," *Philosophical Transactions*, 1809, vol. 99, pp. 32–38.

[14] Humphrey Davy, "On Some New Electrochemical Researches, on Various Objects, Particularly the Metallic Bodies, from the Alkalies and Earths, and on Some Combinations of Hydrogene," *Philosophical Transactions*, 1810, vol. 100, pp. 16–74.

[15] Humphrey Davy, "Electro-Chemical Researches on the Decomposition of the Earths; with Observations on the Metals Obtained from the Alkaline Earths, and on the Amalgam Procured from Ammonia," *Philosophical Transactions*, 1808, vol. 98, pp. 333–370.

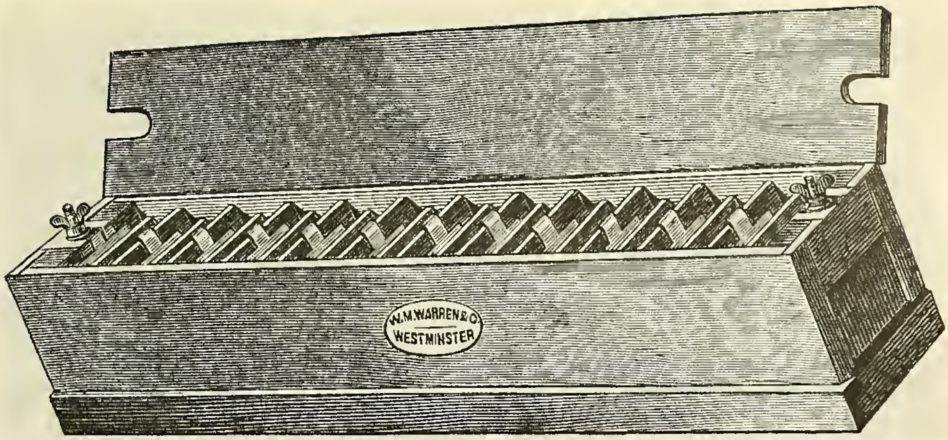

Figure 8.—Fuller's trough battery, a Daniell cell battery that was used in the early days of British telegraphy. From R. Wormell, *Electricity in the Service of Man*, London and New York, 1886, p. 397.

called the "intensity of the electrical force" (that is, the voltage) *n*-fold over that produced by a single pair of electrodes, but the quantity of electricity (that is, the current) was the same whether the pile had one pair or *n* pairs. Davy argued that the intensity of electricity increased with the number of pairs and the quantity increased with the area of these pairs.[16] In 1815 J. G. Children [17] published the results of a number of experiments made to prove Davy's hypothesis. He improved the trough battery by applying a suggestion by William Wollaston to increase the area of one electrode by folding it into a U-shape about the other (fig. 12). Two years later Hans Oersted [18] reported he had increased the effective area of a battery by replacing the wooden trough with a copper one (fig. 13). This copper trough served as one electrode; the electrodes of the other metal were placed in the trough. Such a design greatly increased the heating and sparking power of the battery.

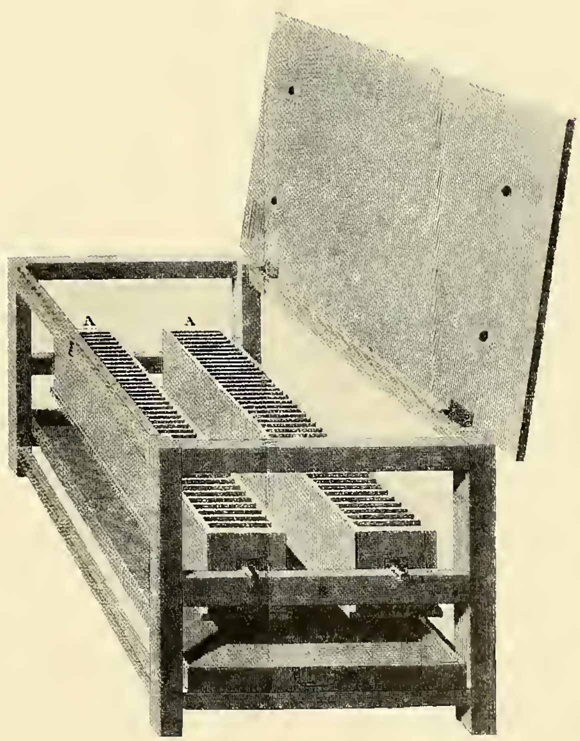

Figure 9.—Pepys' trough battery. From *Philosophical Magazine*, 1803, vol. 15, pl. 1.

[16] Humphrey Davy, "On Some Chemical Agencies of Electricity," *Philosophical Transactions*, 1807, vol. 97, pp. 1–56.

[17] John G. Children, "An Account of Some Experiments with a Large Voltaic Battery," *Philosophical Transactions*, 1815, vol. 105, pp. 363–374.

[18] Hans C. Oersted, "Bemerkungen hinsichtlich auf Contactelektrizität," *Journal für Chemie und Physik* (hereinafter referred to as Schweigger's *Journal*), 1817, vol. 20, pp. 205–212.

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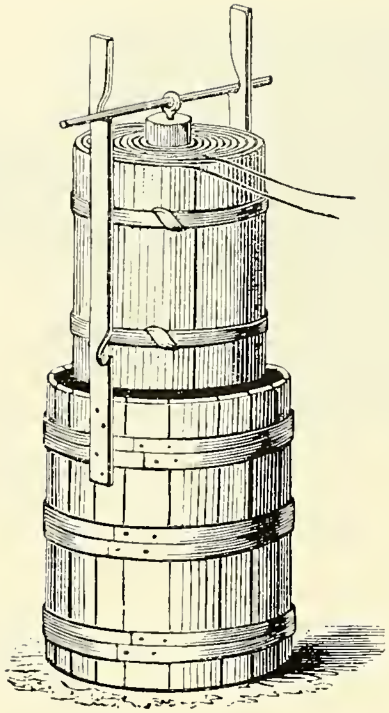

Figure 10.—Pepys' plunge battery as constructed for the Royal Institution. From H. M. Noad, *Student's Textbook of Electricity*, London, 1867, p. 168.

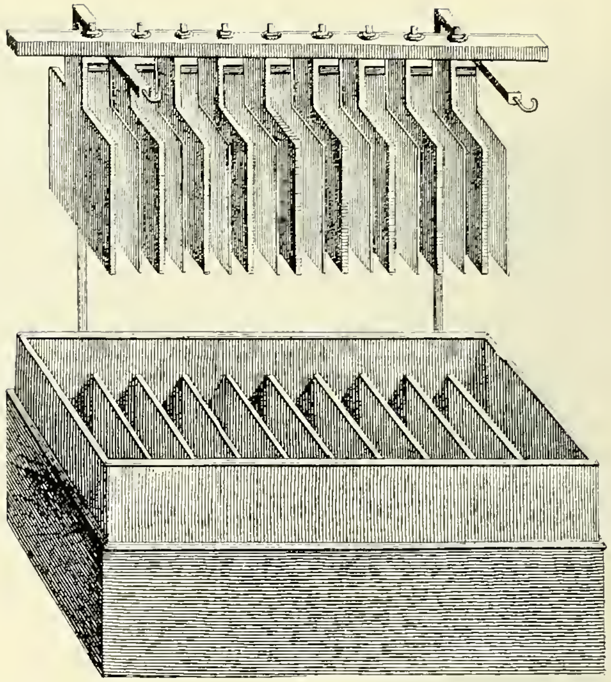

Figure 11.—One of the 200 plunge batteries in the "Great Battery" of the Royal Institution. From *Philosophical Transactions of the Royal Society of London*, 1810, vol. 100, pl. 2, fig. 6.

Robert Hare [19] tried to attack the problem on a more general basis. He made what he called a "calorimotor" by connecting all the copper plates together and all the zinc plates together, so that "instead of multiplying the pairs of galvanic plates [he increased the effect] by enlarging one pair" (fig. 14). He further increased the area of the electrodes that would fit in a given volume by rolling them up in a close spiral. His "galvanic deflagrator" [20] simplified battery construction in the same manner as had Oersted's copper trough battery. Instead of a cell for each pair of elements, only one trough was used. Michael Faraday, Peter Barlow, and Joseph Henry all used batteries based on the construction of Hare's calorimotor for their experiments.

Due to the nullifying chemical reactions of polarization and local action, both the trough battery and the plunge battery had extremely limited lives. Local action results from the use of impure metals, where the impurity forms a voltaic pair with the material of the electrode and prevents the affected portion of the electrode from contributing to the electrical output of the cell. Since over half the energy, and in some cases as much as three-quarters of the energy, of the zinc electrode could be wasted in local action, the impure zinc that was available commercially at the time led to considerable inefficiency.

Auguste de la Rive found that electrodes made from distilled zinc would eliminate local action, but the method was too expensive for ordinary purposes. However, the application of mercury to the zinc electrode permitted the zinc to interact with the electrolyte and at the same time prevented the im-

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[19] Robert Hare, "A New Theory of Galvanism, Supported by Some Experiments and Observations Made by Means of the Calorimotor, a New Galvanic Instrument," *American Journal of Science*, 1819, vol. 1, pp. 413–423.

[20] Robert Hare, "A Memoir on Some New Modifications of Galvanic Apparatus, with Observations in Support of His New Theory of Galvanism," *American Journal of Science*, 1821, vol. 3, pp. 105–117. "Correspondence between Robert Hare . . . and the Editor, on the Subject of Dr. Hare's Calorimotor and Deflagrator, and the Phenomena Produced by Them," *American Journal of Science*, 1822, vol. 5, pp. 94–112.

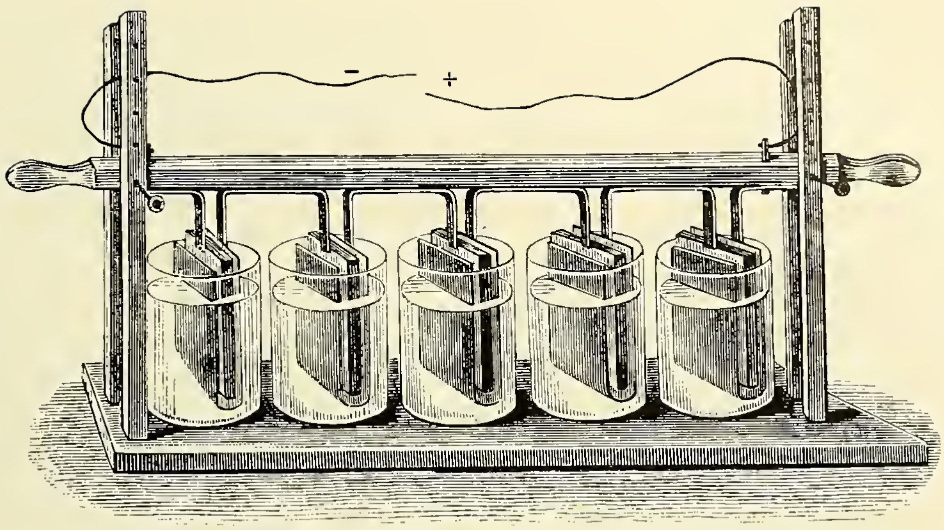


Figure 12.—Plunge battery using Wollaston's U-shaped electrodes. From T. Karass, *Geschichte der Telegraphie*, Braunschweig, 1909, p. 55.

purities from doing so. Although Davy casually mentioned the use of such an amalgamated electrode in his Bakerian Lecture[21] of 1826, De la Rive was the first to examine and explain the relation between amalgamation and local action.[22] (It may be that Davy was led to try such electrodes by analogy with the use of amalgamated electrodes in the usual electrostatic machine.) K. T. Kemp[23] and William Sturgeon[24] were the first to use amalgamation regularly in their experiments.

Polarization results from the formation of a gaseous or solid film at an electrode. This film may prevent chemical interaction between the electrode and the electrolyte and may cause a current in the direction opposite to the normal flow.

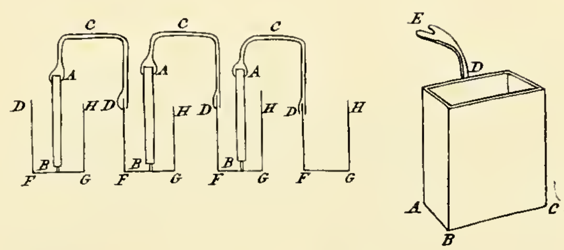


Figure 13.—Oersted's trough battery. From Schweigger's *Journal für Chemie und Physik*, 1817, vol. 20, fig. 2 of plate in Heft 2.

One of the first practical answers to the problem of gaseous polarization was found by J. Frederic Daniell, who in 1836 constructed a cell that used not one electrolyte but two.[25] As early as 1801 Davy had devised a two-solution cell to demonstrate his theory that electricity was the result of chemical oxidation rather

[21] Humphrey Davy, "On the Relations of Electrical and Chemical Changes," *Philosophical Transactions*, 1826, vol. 116, pp. 383–422.

[22] Auguste de la Rive, "Note relative à l'action qu'exerce sur le zinc l'acide sulfurique étendu d'eau," *Bibliothèque universelle, sciences et arts*, 1830, vol. 43, pp. 391–411.

[23] K. T. Kemp, "Description of a New Kind of Galvanic Pile, and also of Another Galvanic Apparatus in the Form of a Trough," *Edinburgh New Philosophical Journal*, 1828, vol. 6, pp. 70–77; "Voltaic Batteries with Amalgamated Zinc," *Annals of Electricity, Magnetism and Chemistry* (hereinafter referred to as Sturgeon's *Annals of Electricity*), 1837, vol. 1, pp. 81–88.

[24] William Sturgeon, "On Electro-Magnets," *Philosophical Magazine*, 1832, vol. 11, pp. 194–205.

[25] J. Frederic Daniell, "On Voltaic Combinations," *Philosophical Transactions*, 1836, vol. 126, pp. 107–124; "Additional Observations on Voltaic Combinations," *Philosophical Transactions*, 1836, vol. 126, pp. 125–129; "Further Observations on Voltaic Combinations," *Philosophical Transactions*, 1837, vol. 127, pp. 141–150.

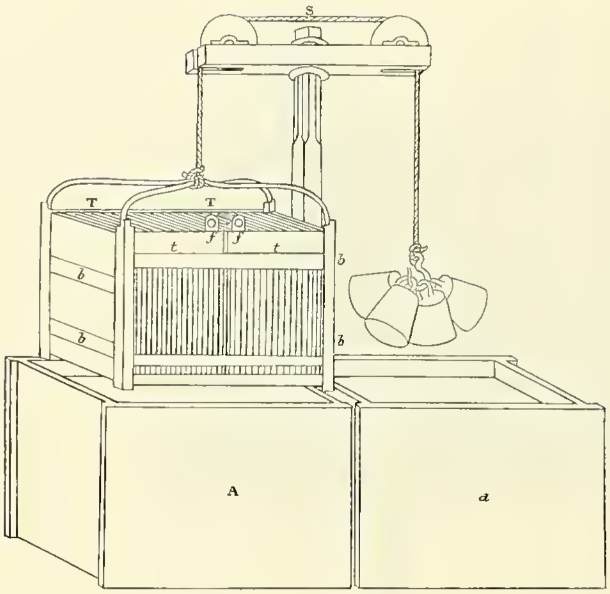
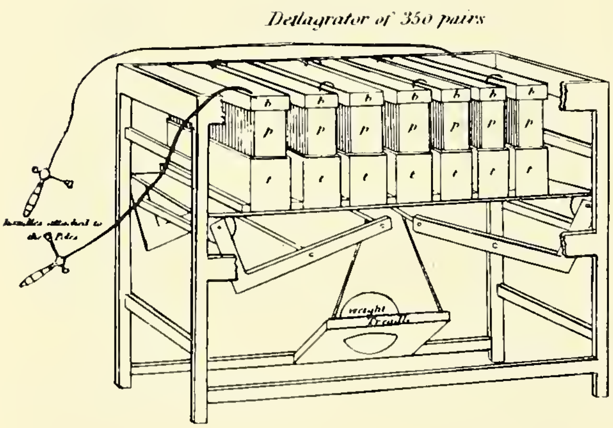


Figure 14.—Robert Hare's calorimotor (top) and galvanic deflagrator. From *American Journal of Science*, 1819, vol. 1, plate opposite p. 413, and 1822, vol. 5, plate opposite p. 95.



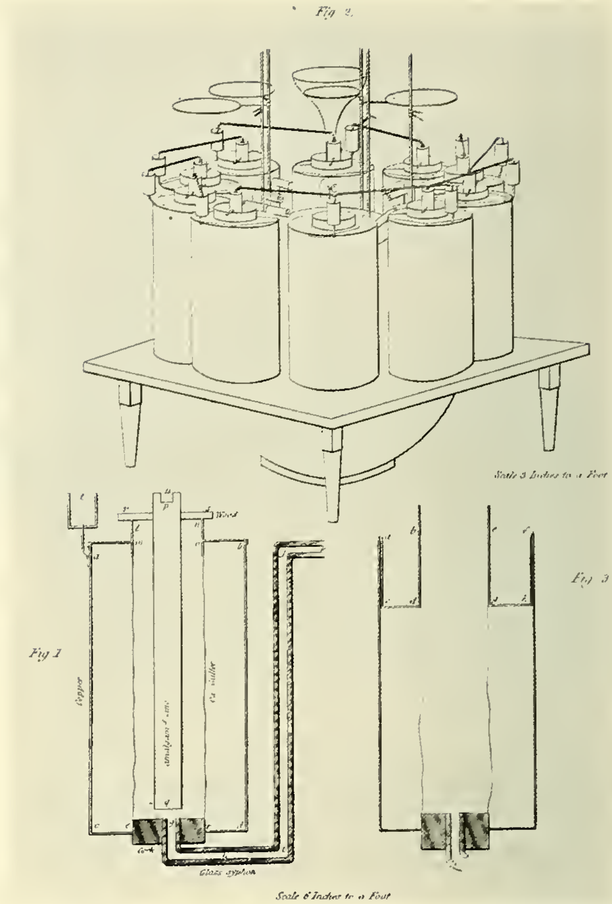


Figure 15.—Daniell's "constant" battery. From *Philosophical Transactions of the Royal Society of London*, 1836, vol. 126, p. 117, pl. 9.

than of physical contact,[26] and Antoine Becquerel had devised another such cell[27] in the 1820's as a result of Davy's theories. Daniell set out to test Faraday's electrochemical theories, and he devised his nonpolarizable "Constant Battery" on the results (figs. 15, 16, and 17). In Daniell's cell an amalgamated zinc electrode in a weak solution of sulfuric acid was separated by an ox gullet from a copper electrode in a copper sulfate solution. John Gassiot made a more durable cell by replacing the gullet by an unglazed porcelain cylinder.[28] While the high internal resistance of the Daniell cell limited the current consider-

[26] Humphrey Davy, "An Account of Some Galvanic Combinations, Formed by the Arrangement of Single Metallic Plates and Fluids, Analogous to the New Galvanic Apparatus of Mr. Volta," *Philosophical Transactions*, 1801, vol. 91, pp. 397–402.

[27] Antoine Becquerel, "Nouveaux Résultats électro-chimiques," *Annales de chimie et de physique*, 1823, vol. 23, pp. 259–260; "De l' Etat de l'électricité développée pendant les actions chimiques, et de la mesure de ces dernières au moyen des effets électriques qui en résultent," *Annales de chimie et de physique*, 1823, vol. 24, pp. 192–205; "Mémoire sur l'électrochimie et l'emploi de l'électricité pour opérer des combinaisons," *Annales de chimie et de physique*, 1829, vol. 41, pp. 5–45.

[28] John P. Gassiot, "Account of Experiments with Voltameters, Having Electrodes Exposing Different Surfaces," *London and Edinburgh Philosophical Magazine and Journal of Science* (title varies, hereinafter referred to as *Philosophical Magazine*), 1839, vol. 13, pp. 436–439.

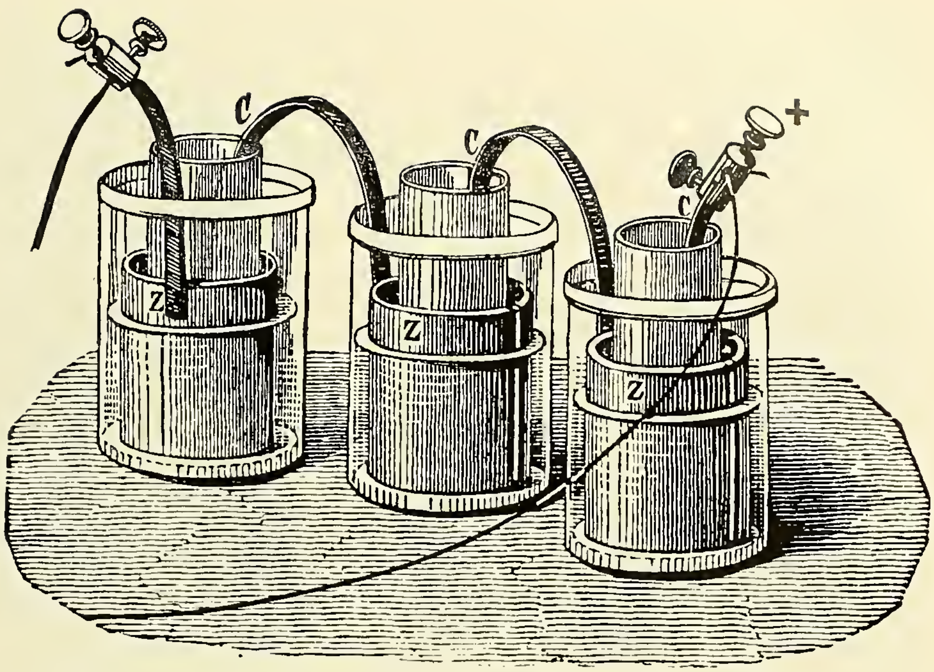


Figure 16.—Laboratory battery of Daniell cells. From A. Niaudet, *Electric Batteries*, New York, 1880, p. 86.

ably and the potential was only 1.1 volts, this voltage was so reliable and unchanging that it was used as a standard up through the 1870's. A simpler version of the Daniell cell, the "gravity" cell, was worked out in the 1850's by Cromwell F. Varley in England and by Heinrich Meidinger[29] in Germany. Meidinger's three forms of the Daniell cell are shown in figure 18. In these later cells the different densities of the two fluids prevented them from mixing. A. Callaud[30] reduced the cell to its simplest form (fig. 19), and a version of this, called the "crowfoot" cell, was occasionally seen until quite recently. The gravity cell was used in the early days of telegraphy and railroad signaling where there were closed circuits with a constant but light drain on the cell.

William Grove[31] devised another variation of a cell of two solutions separated by a porous diaphragm (figs. 20, 21). He used zinc in dilute sulfuric acid and platinum in strong nitric acid. The 1.9-volt output of the Grove cell was almost double the output of the Daniell cell, and its low internal resistance enabled it to give currents as high as 10 amperes. However, the Grove cell was expensive to make, and it gave off highly corrosive fumes. It occurred to a number of researchers[32] to replace the platinum electrode by a cheaper material, but credit for this innovation is usually given to the German chemist Robert Bunsen[33] who modified the Grove cell by replacing the platinum electrode with a charcoal rod and by replacing the nitric acid with fuming nitric acid (fig. 22). The Bunsen cell's voltage was slightly less than that of the Grove cell, but its current was doubled, and it was much cheaper to make.

[29] French Patent 38820, November 22, 1858; Heinrich Meidinger, "Über eine völlig konstante galvanische Batterie," *Annalen der Physik und Chemie* (title varies, hereinafter referred to as *Annalen der Physik*), 1859, vol. 108, pp. 602–610.

[30] French Patent 36643, May 19, 1858.

[31] W. R. Grove, "On a New Voltaic Combination," *Philosophical Magazine*, 1838, vol. 13, pp. 430–431; "On a Small Voltaic Battery of Great Energy; Some Observations on Voltaic Combinations and Forms of Arrangement; and on the Inactivity of a Copper Positive Electrode in Nitro-Sulfuric Acid," *ibid.*, 1839, vol. 15, pp. 287–293.

[32] For example, J. T. Cooper, "On the Employment of Carbon in Voltaic Combinations," *Philosophical Magazine*, 1840, vol. 16, pp 35–37; and Silliman, *op. cit.* (footnote 9).

[33] Robert Bunsen, "Ueber die Anwendung der Kohle zur Volta'schen Batterie," *Annalen der Physik*, 1841, vol. 54, pp. 417–420; "Ueber Bereitung einer das Platin in der Grove'schen Kette ersetzenden Kohle," *Annalen der Physik*, 1842, vol. 55, pp. 265–276.

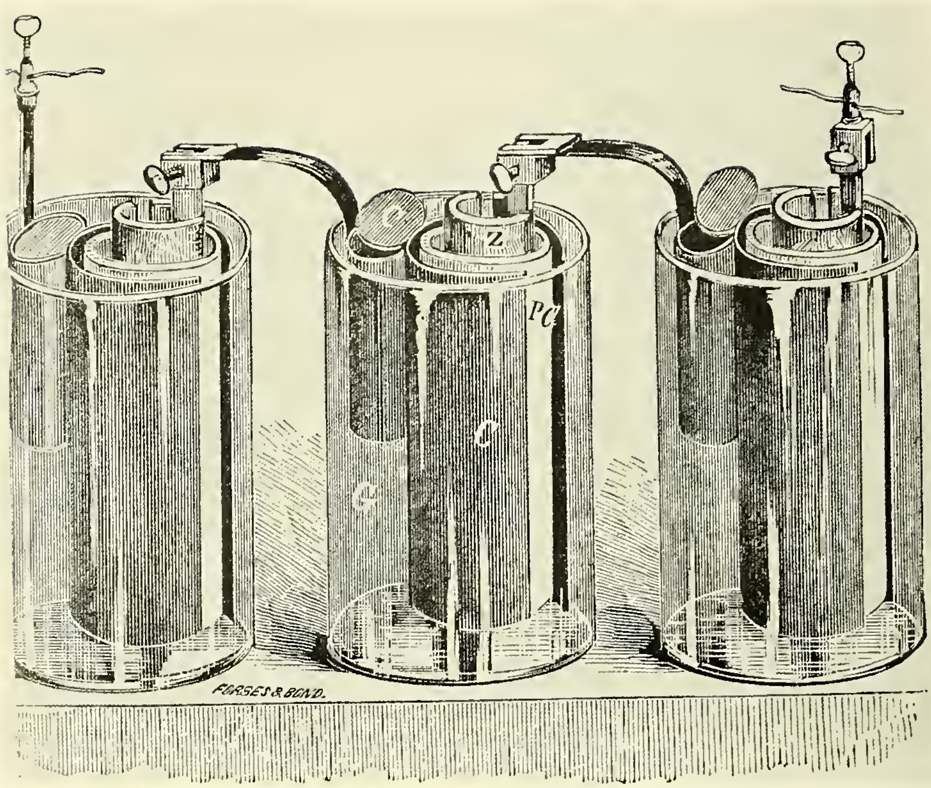


Figure 17.—Battery of Daniell cells as used in American telegraphy. From G. B. Prescott, *History, Theory, and Practice of the Electric Telegraph*, Boston, 1860, p. 27.

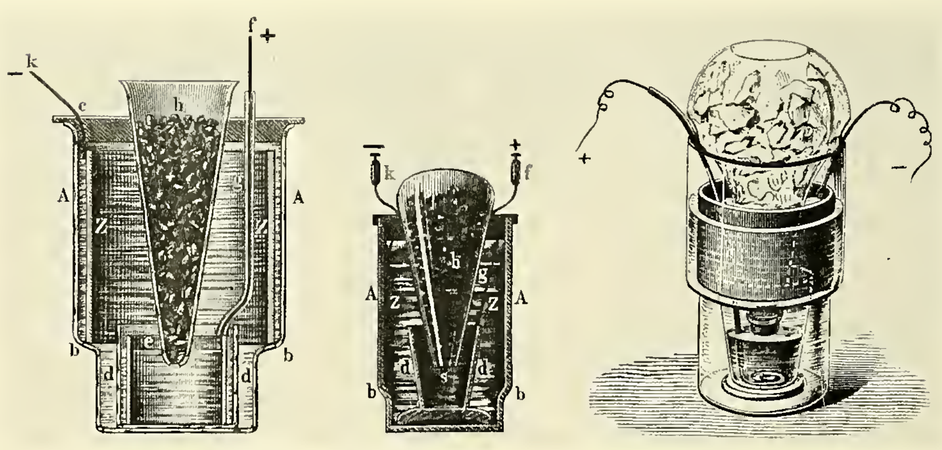


Figure 18.—Meidinger's three forms of the Daniell cell. From T. Karass, *Geschichte der Telegraphie*, Braunschweig, 1909, p. 68.

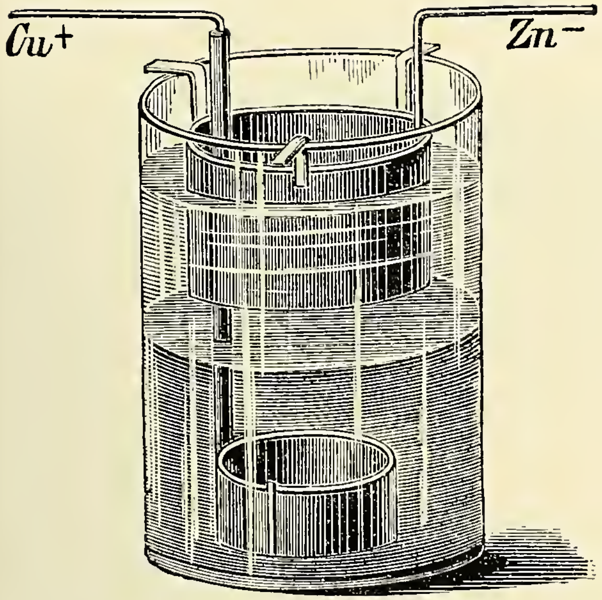


Figure 19.—Callaud's version of the Daniell cell. From R. Wormell, *Electricity in the Service of Man*, London and New York, 1886, p. 401.

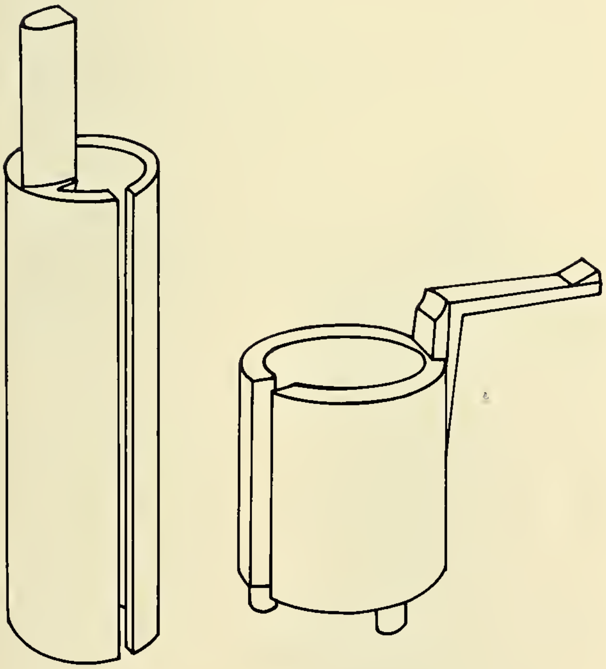


Figure 20.—Shape of the electrodes in a Grove cell. After G. B. Prescott, *History, Theory, and Practice of the Electric Telegraph*, Boston, 1860, p. 29, fig. 9.

Despite its strong fumes, the Bunsen cell was widely used.

The Daniell and Grove cells avoided polarization by the use of two solutions. Other nonpolarizing cells using only a single solution also were invented. Alfred Smee [34] made such a single-solution cell by placing a pair of amalgamated zinc plates in dilute sulfuric acid with a platinum (later silver) plate covered with finely divided platinum (figs. 23, 24). While the voltage of Smee's cell was only about half a volt, it had the advantage of a low cost of maintenance and could be used for open-circuit work where there was a very light drainage of current. Bunsen in 1841 [35] and R. Warrington in 1842 [36] invented one-solution cells that eliminated polarization by using zinc and carbon electrodes in a bichromate and sulfuric acid solution (fig. 25). About the same time J. C. Poggendorff tried a chromic acid cell in his laboratory.[37] The Poggendorff cell gave about two volts, and its low internal resistance enabled it to give high currents for a short period of time. The cell recovered its low resistance on open circuit. Grenet, a Frenchman, devised a bottle version of the chromic acid cell that was widely used in the 1860's (fig. 26). This is the cell that one sees in so many of the physics textbooks of the second half of the 19th century.

After midcentury, when electricity was beginning to pass from the laboratory stage to that of industrial application, more rugged versions of the voltaic cell appeared. The development of a storage battery began in 1859 when Gaston Planté decided to compare the polarization resulting from solid films on electrodes of various metals.[38] With his discovery that lead electrodes gave a more intense and longer-lasting secondary current than electrodes of other metals,

[34] Alfred Smee, "On the Galvanic Properties of the Metallic Elementary Bodies, with a Description of a New Chemico-Mechanical Battery," *Philosophical Magazine*, 1840, vol. 16, pp. 315–321.

[35] Bunsen, *op. cit.* (footnote 33), and "Spectralanalytische Untersuchungen," *Annalen der Physik*, 1875, vol. 155, pp. 230–252.

[36] R. Warrington, "On the Employment of Chromic Acid as an Agent in Voltaic Arrangements," *Philosophical Magazine*, 1842, vol. 20, pp. 393–395; Leeson, in *Philosophical Magazine*, 1842, vol. 20, p. 262.

[37] J. C. Poggendorff, "Über die mit Chromsäure konstruirten galvanischen Ketten," *Annalen der Physik*, 1842, vol. 57, pp. 101–111.

[38] Gaston Planté "Note sur la polarisation voltaïque," Académie des Sciences, Paris, *Comptes rendus*, 1859, vol. 49, pp. 402–405.

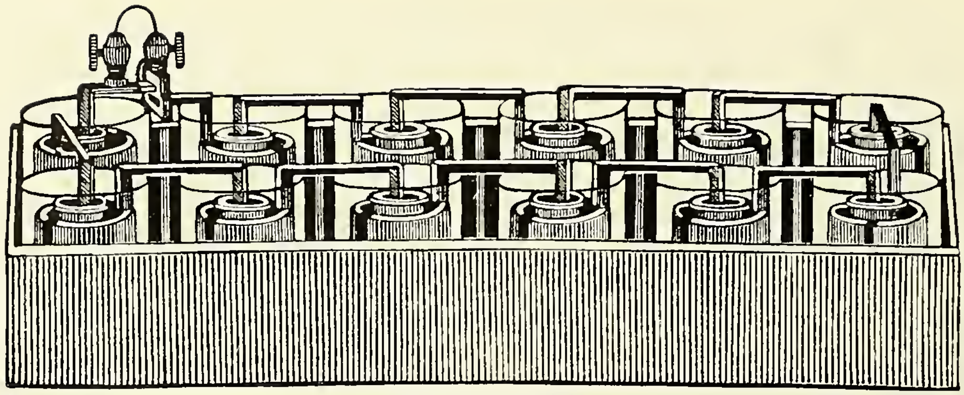


Figure 21.—Grove battery as used in American telegraphy. From G. B. Prescott, *History, Theory, and Practice of the Electric Telegraph*, Boston, 1860, p. 68, fig. 7.

Planté was able to turn the disadvantage of polarization into an advantage, and, using solid electrodes—Grove's 1839 cell had gas electrodes—he created the first "storage" (secondary) cell.[39] By electrolyzing dilute sulfuric acid with lead electrodes, Planté formed a layer of lead oxide on lead. The charging batteries were then removed, and the secondary cell could return the stored energy. If not too much current was required, Planté's cell gave a somewhat constant potential of 1.5 volts. (Figs. 27–31).

Camille Faure modified the secondary cell by applying a paste of the red oxide of lead directly to the plates.[40] The cell was charged by electrolyzing dilute sulfuric acid with these preformed electrodes. This process converted the red oxide to lead dioxide, and the cell was ready for use (fig. 32). The Faure cell gave two volts and had a more stable operation than did the Planté cell. It appeared at a very opportune time, for it found immediate application in telegraphy; later it was particularly important in the production of electrical power. Use of the secondary battery to store electricity when the load was light and to deliver it to the system when the load was heavy resulted in a one-third reduction in the cost of electrical power.

Since secondary cells using acid electrolytes were difficult to work with, some inventors turned to alkaline electrolytes. Felix de Lalande and G. Chaperon invented a cell that used iron or copper for one electrode and zinc for the other, copper oxide as a depolarizer, and a caustic soda or potash solution for the electrolyte.[41] The potential was only about one volt, but the low internal resistance of this cell enabled it to produce high currents.

[39] Gaston Planté, "Nouvelle Pile secondaire d'une grande puissance," Académie des Sciences, Paris, *Comptes rendus*, 1860, vol. 50, pp. 640–642; "Recherches sur les courants secondaires et leurs applications," *Annales de chimie et de physique*, 1868, vol. 15, pp. 5–30; *Recherches sur l'électricité*, Paris, 1879.

[40] C. A. Faure, "Sur La Pile secondaire de M. C. Faure," Académie des Sciences, Paris, *Comptes rendus*, 1881, vol. 92, pp. 951–953.

[41] Félix de Lalande and G. Chaperon, "Nouvelle Pile à oxyde de cuivre," Académie des Sciences, Paris, *Comptes rendus*, 1883, vol. 97, pp. 164–166.

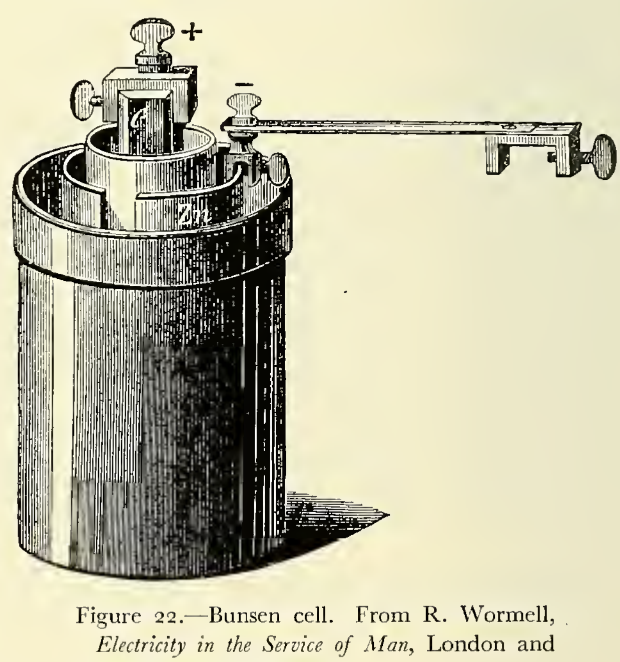


Figure 22.—Bunsen cell. From R. Wormell, *Electricity in the Service of Man*, London and New York, 1886, p. 404.

Thomas A. Edison designed a variation of the Lalande-Chaperon cell in 1889,[42] but later he invented another form of alkaline accumulator (fig. 34). Nickel-plated steel electrodes were covered with nickel peroxide and graphite to form the anode, and with finely divided iron and graphite to form the cathode. The electrolyte was again a solution of caustic potash. The very high currents that could be drawn by the Edison cell made it practical for use in electric traction. In Edison's cell—a form of which is still used—the voltage was about 1.3 volts, and the current was even higher than that of the Lalande-Chaperon cell.

The dry cell began with the 1868 cell of Georges Leclanché,[43] which used a solid depolarizer (figs. 33, 35). In the Leclanché cell, a carbon electrode was inserted into a pasty mixture of manganese dioxide and other materials. A zinc electrode in a sal ammonic solution was separated from this mixture by a ceramic cylinder. This cell gave 1.5 volts, but its pasty texture and its high internal resistance limited it to intermittent use, and its current strengths were not too high. However, it was used extensively in the 19th century for telegraph and telephone lines and for other signaling systems. The ancestor of the modern dry cell was C. Gassner's modification[44] (fig. 36) of the Leclanché cell. The electrical characteristics and uses of the Gassner cell were similar to those of the Leclanché cell. A paste of zinc oxide, sal ammoniac, plaster, and zinc chloride formed the electrolyte; and the zinc electrode formed the container. Commercial production of such dry cells began about 1890.

After the middle of the 19th century, standardization of voltages became an increasingly important and, at the same time, difficult problem. At first the Daniell cell was used to provide a reference voltage, but in 1873 J. Latimer Clark[45] devised an even more stable cell (fig. 37). The potential of the Clark cell was reproducible to an accuracy of one-tenth of 1 percent, and its use slowly spread. However, by the turn of the century the Clark cell began to be supplanted by E. Weston's standard cell,[46] which finally replaced

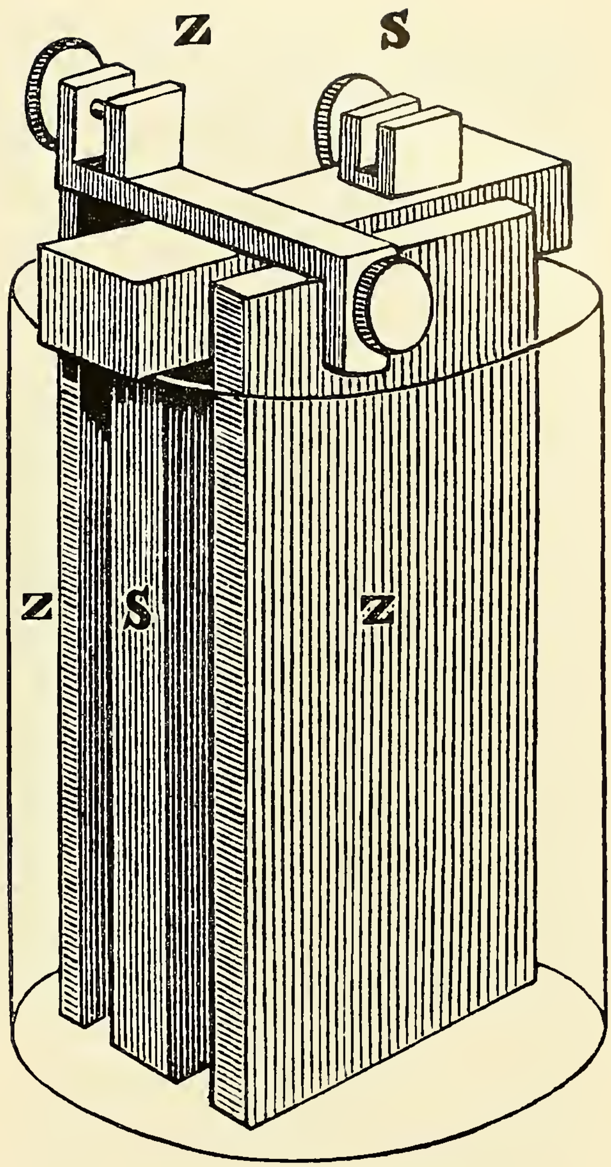


Figure 23.—Smee cell. From F. C. Bakewell, *Manual of Electricity*, London and Glasgow, 1859, p. 147.

[42] U.S. Patent 430279, June 15, 1889; A. E. Kennelly, "The New Edison Storage Battery," *Electrical World*, 1901, vol. 37, pp. 867–869.

[43] Georges Leclanché, "Pile au peroxyde de manganèse à seul liquide," *Les Mondes*, 1868, vol. 16, pp. 532–535.

[44] German Patent 45251, 1887. See also, "Gassner's Dry Battery" in *Electrician*, 1888, vol. 21, pp. 245–246, 703–704; 1889, vol. 24, p. 185; 1890, vol. 25, p. 508; 1892, vol. 28, pp. 643–644; and Heinrich Krehbiel, "Vergleichende Untersuchung von Trockenelementen," *Elektrotechnische Zeitschrift*, 1890, vol. 11, pp. 422–427.

[45] J. Latimer Clark, "On a Voltaic Standard of Electromotive Force," *Proceedings of the Royal Society of London*, 1872, vol. 20, pp. 444–448; "On a Standard Voltaic Battery," *Philosophical Transactions*, 1874, vol. 164, pp. 1–14; Lord Rayleigh and Mrs. Sidgwick, "On the Electro-Chemical Equivalent of Silver and on the Absolute Electro-Magnetic Force of Clark Cells," *Philosophical Transactions*, 1884, vol. 175, pp. 411–460.

[46] U.S. Patent 494827, April 4, 1893.

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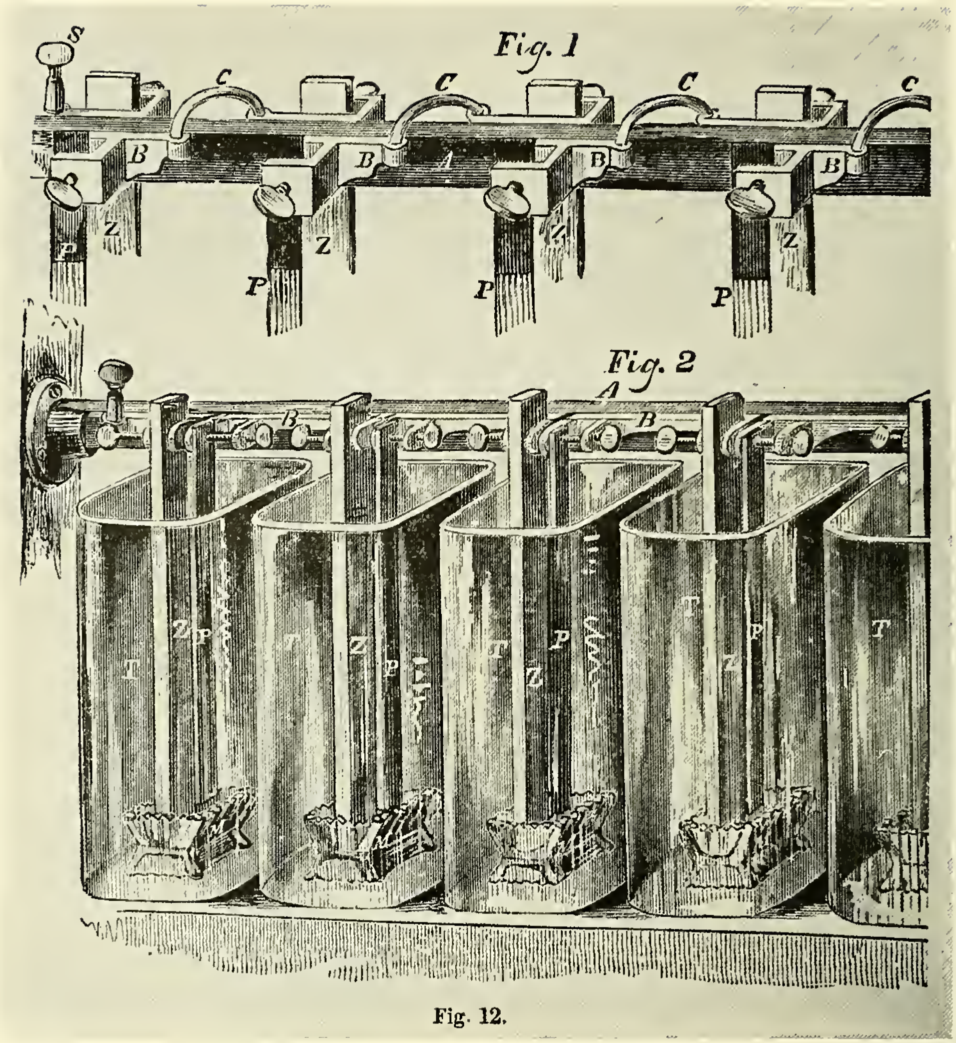


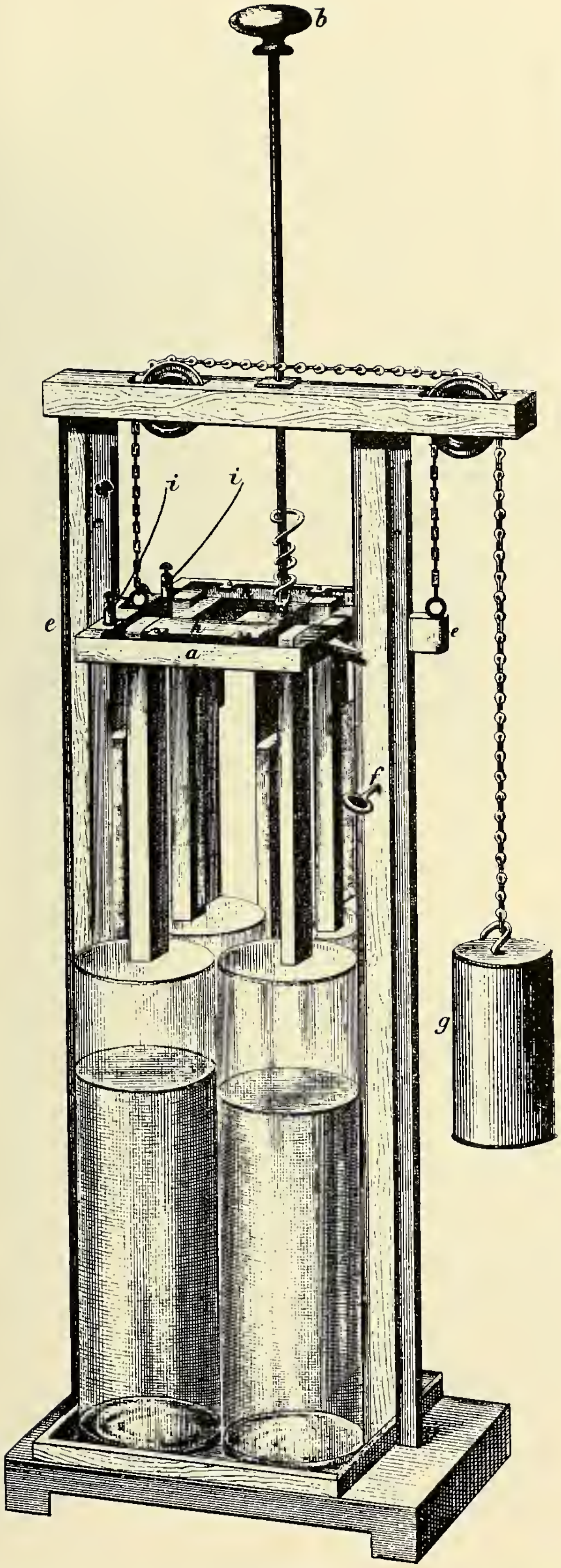
Figure 24.—Battery of Smee cells as used in American telegraphy. From G. F. Prescott, *History, Theory, and Practice of the Electric Telegraph*, Boston, 1860, p. 33.

the Clark cell entirely. One of the earliest Weston cells used by the National Bureau of Standards is shown in figure 38.

ELECTROCHEMISTRY

Almost as soon as a source of electrical current was invented by Volta, the chemical effects of this current were noticed. Among the first to remark these effects were Nicholson and Carlisle, in 1800.[47] They used a drop of water on the top of their pile to ensure a good electrical contact and noticed that gases were evolved in the drop. On the basis of the odors (!) of the gases they identified them as hydrogen and oxygen. They then went on to obtain silver, lead and copper from solutions of the compounds of these metals. In the same year, and independently, the Bavarian Johann

[47] Nicholson, *op. cit.* (footnote 6); Carlisle, Cruickshanks, Nicholson, *et al.*, "Experiments in Galvanic Electricity," *Philosophical Magazine*, 1800, vol. 7, pp. 337–347.



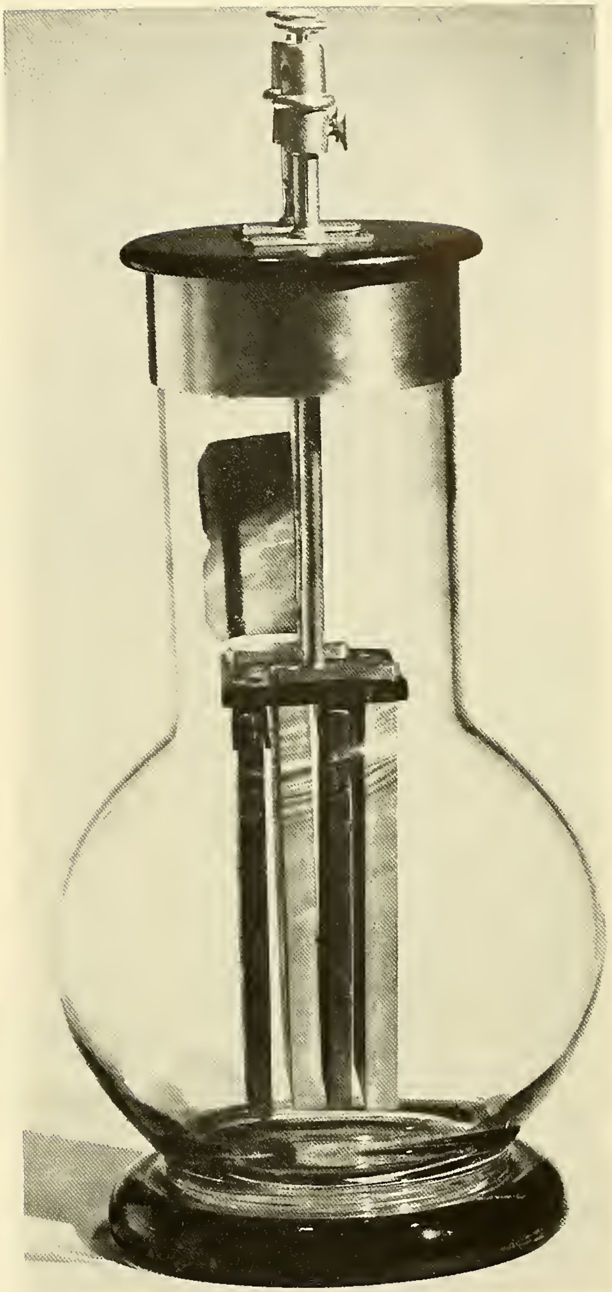


Figure 26.—Grenet cell. (*USNM 315801, Smithsonian photo* 47106.)

Figure 25.—Battery of Bunsen's chromic acid cells. From *Annalen der Physik*, 1875, vol. 155, pl. 8, fig. 2.

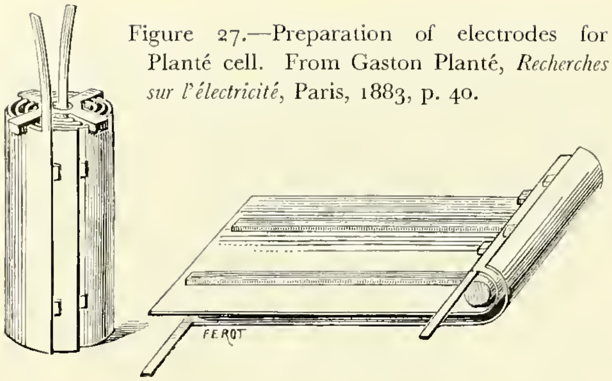


Figure 27.—Preparation of electrodes for Planté cell. From Gaston Planté, *Recherches sur l'électricité*, Paris, 1883, p. 40.

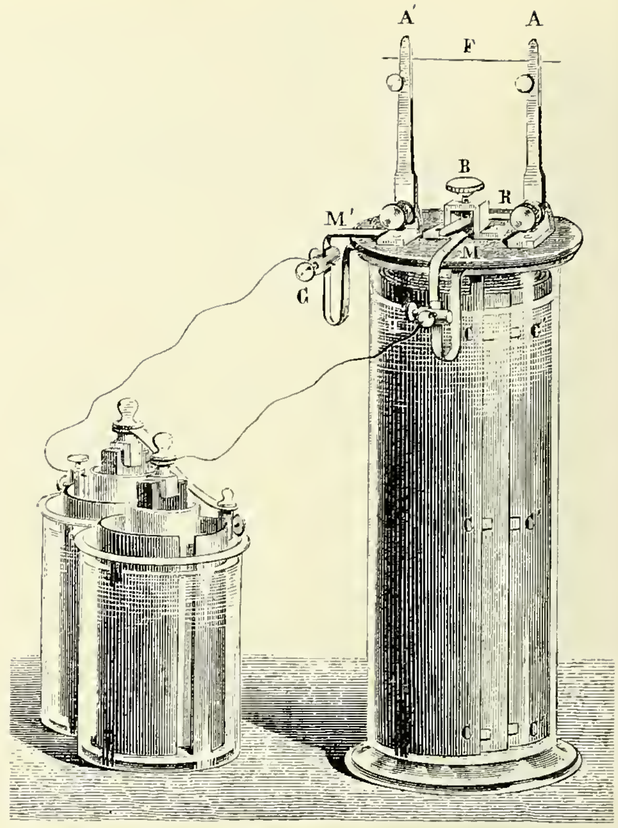


Figure 29.—Charging a Planté cell with a Bunsen battery. From Gaston Planté, *Recherches sur l'électricité*, Paris, 1883, p. 43.

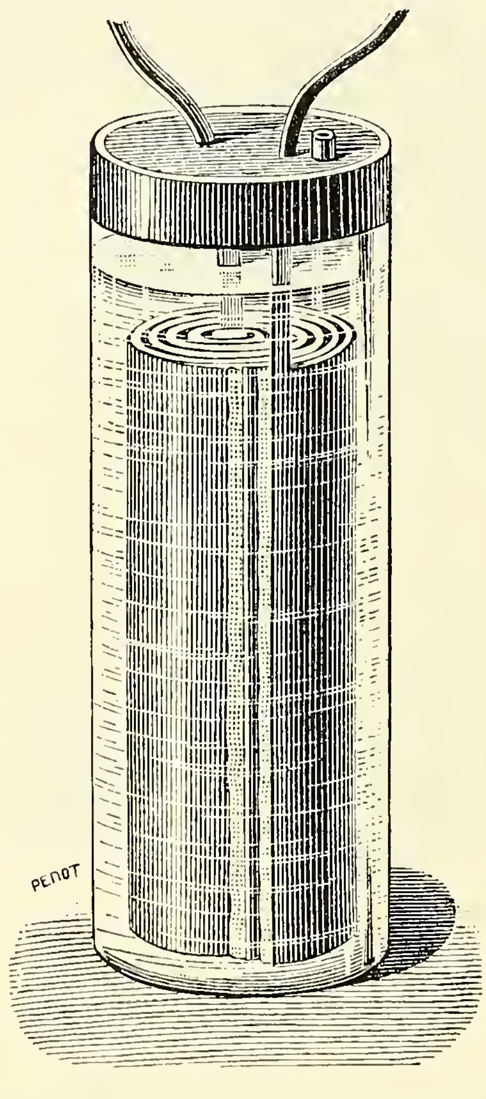


Figure 28.—Planté cell. From Gaston Planté, *Recherches sur l'électricité*, Paris, 1883, p. 35.

Ritter, using the galvanic current, electrolyzed water and precipitated metals from their solution.[48]

The interesting results of Nicholson and Carlisle led to similar experiments on a larger scale, and it was not long before the new force of electricity was replacing fire as a means of analyzing a chemical compound into its elements. In 1807 Humphrey Davy,[49] as mentioned earlier, tried the action of the voltaic current on soda and potash and so discovered two new metals—sodium and potassium. In order to prove his results, Davy successfully reversed this analysis with a synthesis of these oxides. The next year other new elements were discovered: calcium, barium, strontium, and magnesium.[50]

[48] Johann Ritter, "Über den elektrischen oder galvanischen Apparat Volta's und über die chemische Wirkungen der galvanischen Elektrizität, von Nicholson, Cruickshanks und Henry," *Annalen der Physik*, 1800, vol. 6, pp. 468–472.

[49] Davy, *op. cit.* (footnote 11).

[50] Davy, *op. cit.* (footnote 15).

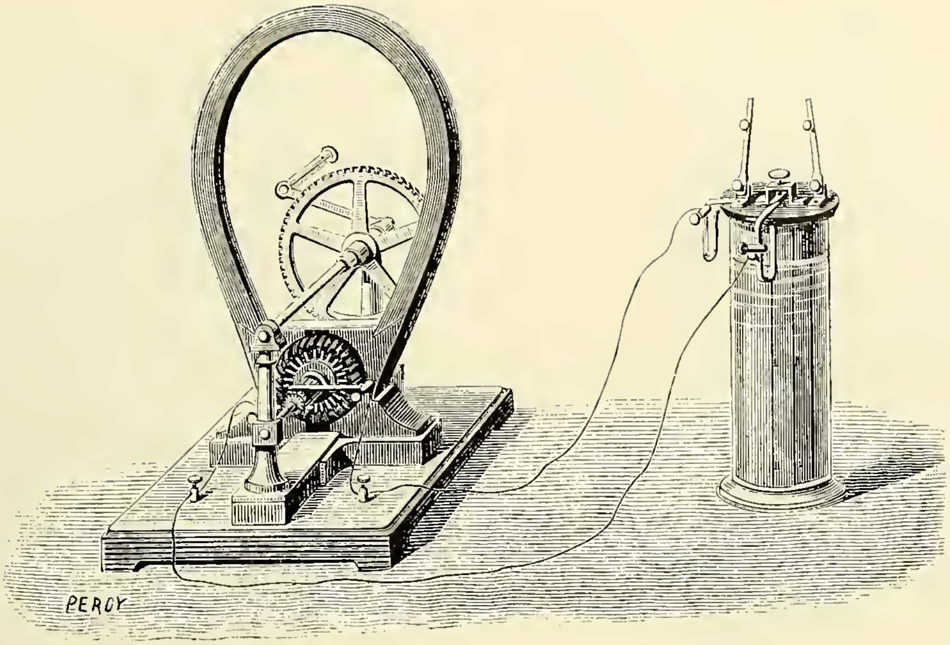


Figure 30.—Charging a Planté cell with a Gramme magneto generator. From Gaston Planté, *Recherches sur l'électricité*, Paris, 1883, p. 80.

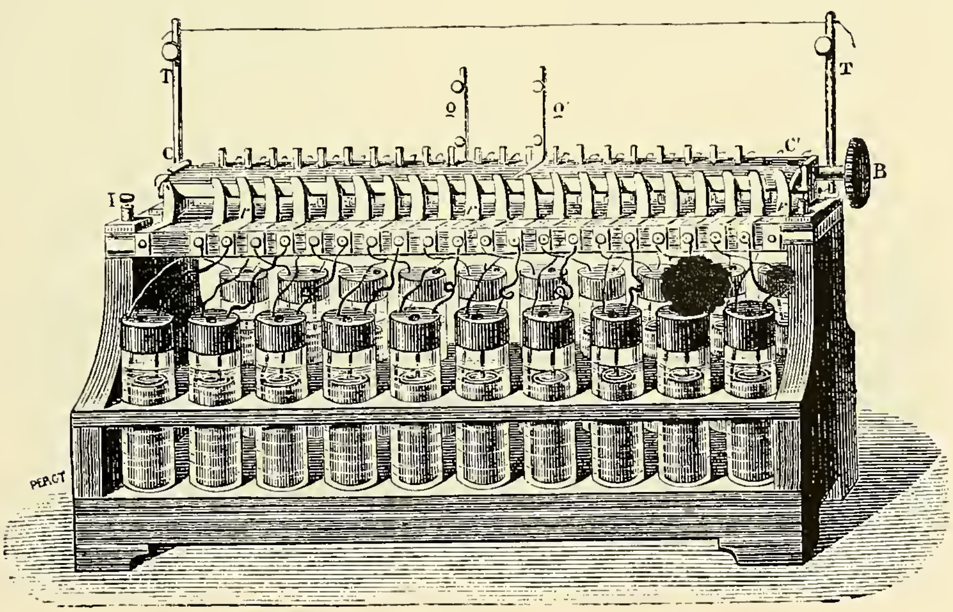


Figure 31.—Battery of Planté cells arranged for high-voltage experiments. From Gaston Planté, *Recherches sur l'Electricité*, Paris, 1883, p. 97.

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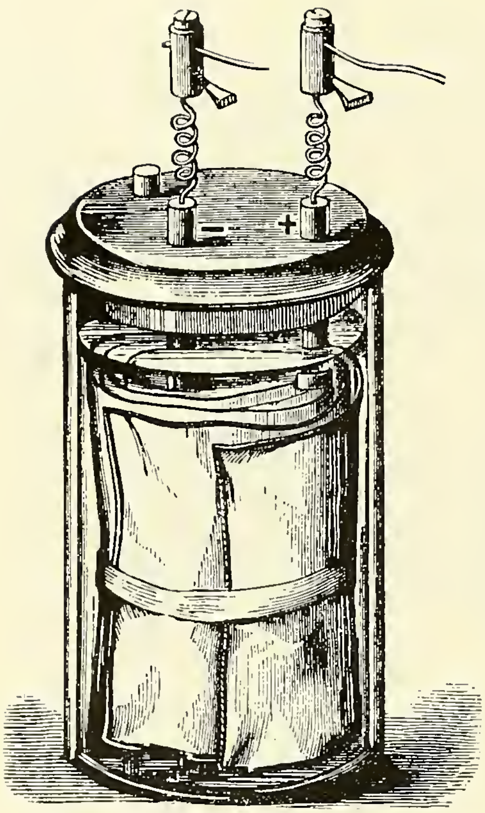

Figure 32.—Faure cell, as modified by Reynier. From R. Wormell, *Electricity in the Service of Man*, London and New York, 1886, p. 438.

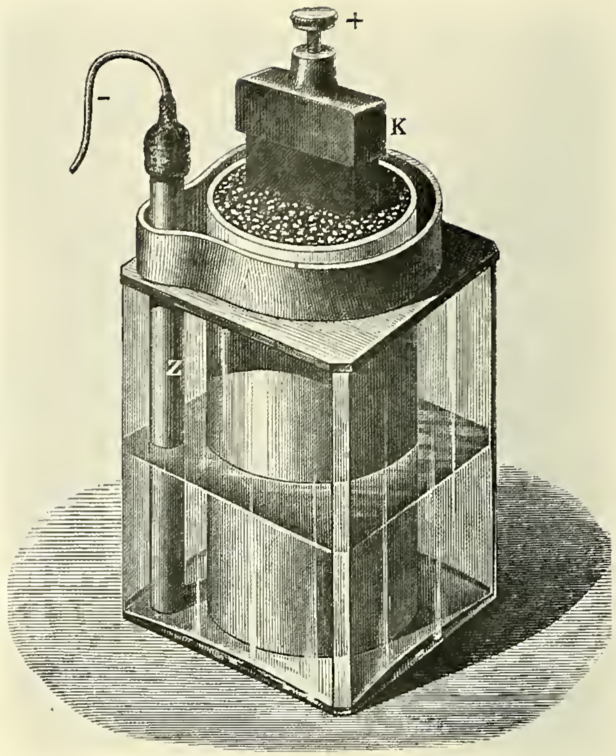

Figure 33.—Leclanché cell. From T. Karass, *Geschichte der Telegraphie*, Braunschweig, 1909, p. 77.

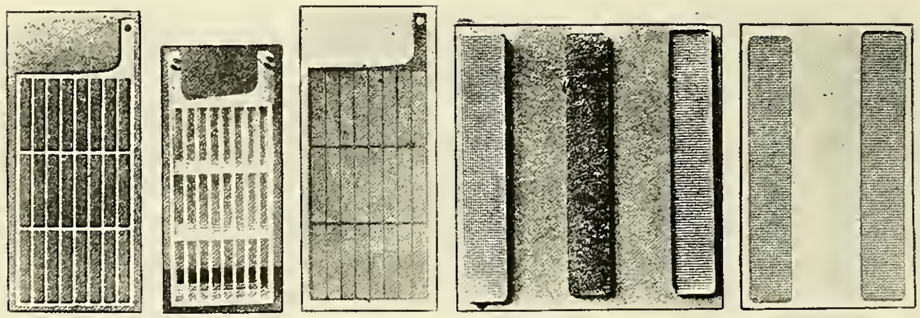

Figure 34.—Electrodes and inserts for Edison storage battery of 1900. From *Electrical World*, 1901, vol. 37, p. 867.

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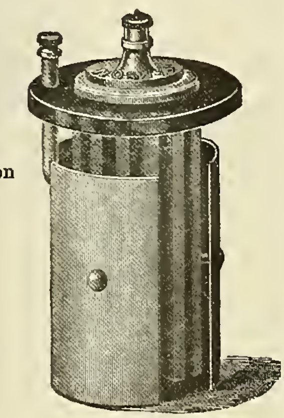

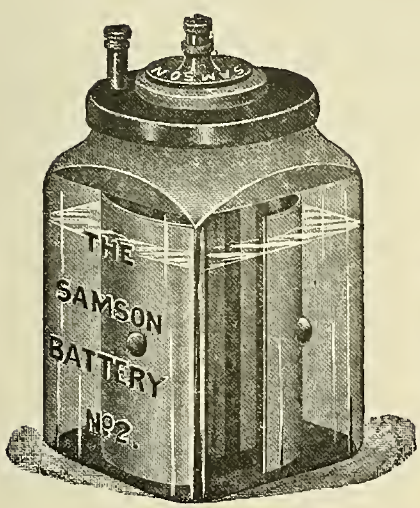

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Figure 35.—This page from an 1892 catalog shows the American version of the Leclanché cell.

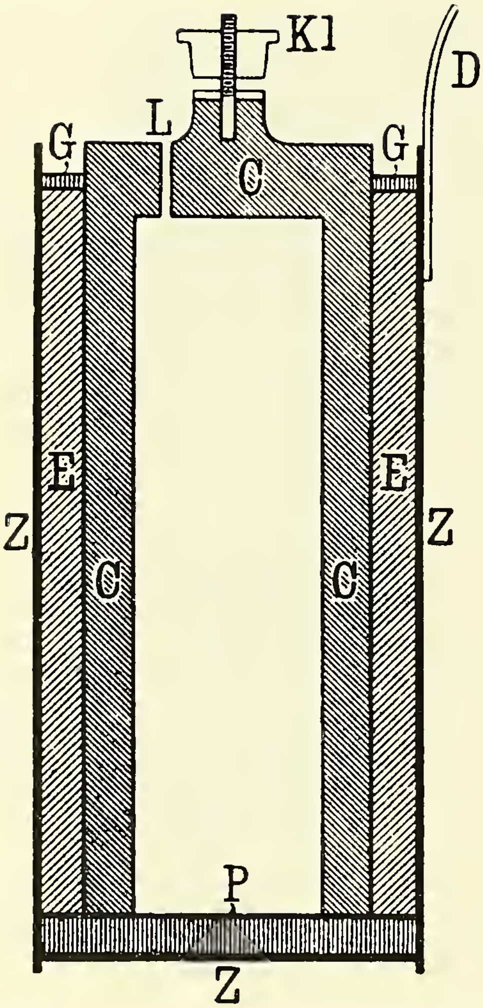

Figure 36.—Gassner's dry cell, 1888. From T. Karass, *Geschichte der Telegraphie*, Braunschweig, 1909, p. 84.

Once cells that produced a lasting current had been invented, the first commercial applications of electricity began to take place.[51] In 1839 M. H. Jacobi introduced electrotyping as a means of accurately reproducing casts and engravings in metal.[52] A short time later, T. Spender and J. Wilson [53] applied for a patent on a similar process in England.

Essentially the same process of electrolysis used in electrotyping was used in electroplating, which appeared commercially at this time. However, it was quite difficult to discover the proper chemical and electrical conditions for electroplating. Auguste de la Rive devised a process to electroplate gold on silver and steel.[54] It has been reported [55] that Jacobi used his electrotyping technique to gild the iron dome of the Cathedral of St. Isaac in St. Petersburg. The Elkington firm in Manchester had started electroplating with zinc as early as 1838. Two years later John Wright of Manchester invented the cyanide process of gold and silver plating and sold it to the pioneering Elkington firm.[56] (This firm also was the first to make commercial use of a generator—for electroplating. The Elkington techniques were introdued into the United States through the Scoville firm [57] in Waterbury, Connecticut.) These new processes of electrotyping and electroplating soon replaced reproduction by stereotype and silver plating by heating silver in intimate contact with copper.

Besides the chemical effects of the electric current, other effects were noticed. One of these was the mechanical effect produced by the galvanic current

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[51] The process of electroplating shares with the electromagnetic telegraph the distinction of having beeen among the first commercially successful applications of the electric current.

[52] M. H. Jacobi, "On the Method of Producing Copies of Engraved Copper-Plates by Voltaic Action; on the Supply of Mixed Gases for Drummond's Light, by Electrolysis; on the Application of Electro-Magnetism as a Motive Power in Navigation, and on Electro-Magnetic Currents," *Philosophical Magazine*, 1839, vol. 15, pp. 161–165.

[53] "A Patent Is Granted to Mr. Spencer and Mr. Wilson, Both of Liverpool, for Certain Improvements in the Process of Engraving on Metals, by Means of Voltaic Electricity," Sturgeon's *Annals of Electricity*, 1841, vol. 7, pp. 380–381.

[54] Auguste de la Rive to Dominique Arago, April 2, 1840, "Sur Un Procédé électro-chimique ayant pour l'objet le dorage de l'argent et du laiton," Académie des Sciences, Paris, *Comptes rendus*, 1840, vol. 10, pp. 578–582; "On the Progress Effected in the Process of Gilding by the Electro-Chemical Method," Sturgeon's *Annals of Electricity*, 1842, vol. 8, pp. 216–219.

[55] Edward H. Knight, *Knight's American Mechanical Dictionary*, 1882, vol. 1, p. 790.

[56] Charles V. Walker, "An Account of a Method of Electro-Gilding and Electro-Plating at the Expense of a Gold or a Silver Anode," *Philosophical Magazine*, 1841, vol. 19, p. 328. Jean B. Dumas, "Rapport sur les nouveaux procédés introduits dans l'art du doreur par MM. Elkington et De Ruolz," Académie des Sciences, Paris, *Comptes rendus*, 1841, vol. 13, pp. 998–1021. George R. Elkington and John De Ruolz, "Report on the New Processes Introduced in the Art of Gilding," Sturgeon's *Annals of Electricity*, 1842, vol. 8, pp. 125–146. *Dictionary of National Biography*, New York, 1921–1922, vol. 6, pp. 658–659 (George R. Elkington). *Journal of the Royal Society of Arts*, December 1, 1865, vol. 14, p. 46 (obituary of George R. Elkington).

[57] P. W. Bishop, "Scoville—The Oldest Brass Company in America." Unpublished manuscript.

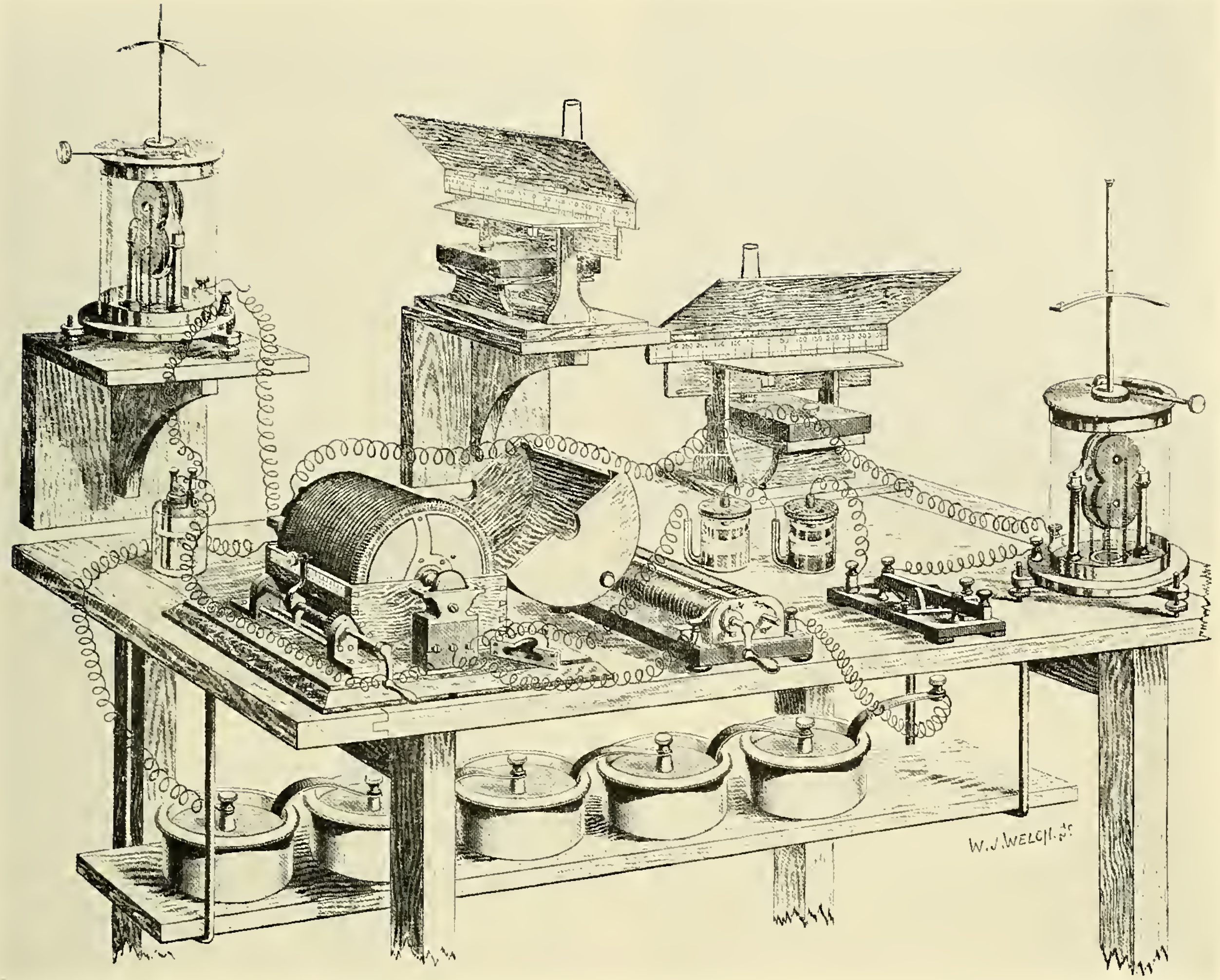

Figure 37.—Calibration of two Clark cells. From *Philosophical Transactions of the Royal Society of London*, 1874, vol. 164, p. 14, fig. 6.

under certain conditions. The possiblilties inherent in such a technique drew the attention of many inventors to the new phenomenon.

The development of steam as a prime mover for factory machinery during the Industrial Revolution and the rapid development of steam locomotives and steamboats during the 30's and 40's of the 19th century made inventors dream of applying the new force of electricity in a similar way to manufacturing and commerce. Before this dream could be realized, however, certain prerequisites had to be fulfilled. A means of applying electrical energy to produce a mechanical force had to be found, a switch had to be devised to make it possible to apply the mechanical force at the right time in the cycle of the motor, and an appropriate recipient for the mechanical force had to be discovered. The invention that enabled man to convert electrical energy into a mechanical force was the electromagnet. The commutator was the switch that determined when the force was applied, and the recipient of the force was the armature. In addition, there had to be devised the most efficient arrangement of electromagnets, commutator, and armature for the production of rotational motion. Actually our modern motor did not develop from the efforts of this period, but such attempts are nonetheless interesting for they reveal the state of electrical technology in the middle of the 19th century.

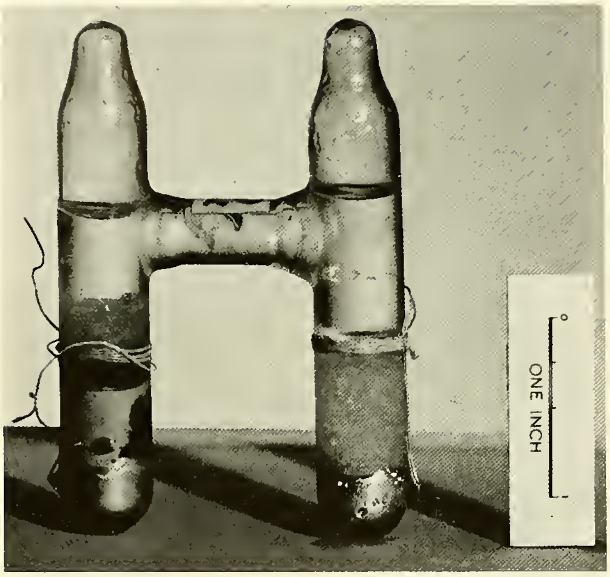

Figure 38.—One of the first Weston cells used by the National Bureau of Standards. (*USNM 316485; Smithsonian photo 46854.*)

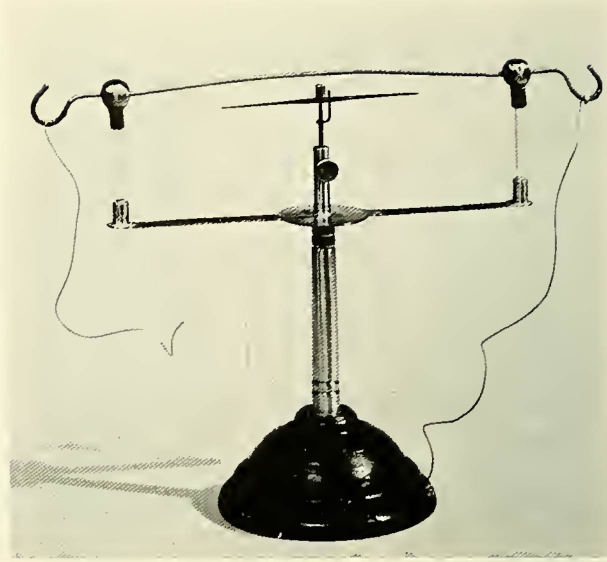

Figure 39.—A model of Oersted's wire experiment. (*USNM 47106–A; Smithsonian photo 31504–A.*)

The Electromagnet

The first step towards the invention of an electromagnet was taken by Hans C. Oersted, a professor of physics at Copenhagen who subscribed to the widely diffused view of the German *Naturphilosoph* that all the forces of nature were somehow related. This belief seemed to Oersted to be borne out especially in the case of electricity and magnetism where the attractions and repulsions followed the same mathematical laws. Other speculators and experimenters had presented what they considered to be proof of a relation between magnetism and electricity, magnetism and light, and electricity and light; but the proof rested on such dubious experiments that most of the prominent scientists of the early 19th century were justifiably skeptical of such an hypothesis. But after many trials Oersted did find a relation between magnetism and electricity when he discovered that a current-carrying conductor, no matter of what material it was made, would cause a magnetic needle in its vicinity to orient itself at right angles to the conductor (fig. 39).

Oersted's brief notice[58] of his discovery was tested within a few weeks by some of the world's leading scientists—by Sir Humphrey Davy[59] at the Royal Institution in London; by Dominique Arago,[60] one of the editors of the *Annales de Chimie et de Physique* at the Académie des Sciences in Paris; by Auguste de la Rive,[61] professor of chemistry at Geneva, Switzerland; by J. S. Schweigger,[62] professor of physics and chemistry at Halle and editor of the *Journal für Chemie und Physik*; and by L. W. Gilbert,[63] professor of physics at the university in Leipzig and editor of the *Annalen der Physik und der physikalischen Chemie.* All of these scientists confirmed Oersted's results.

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[58] Hans Oersted, *Experimenta circa effectum conflictus electrici in acum magneticam*, Hafniae, 1820 (also as an article in many journals such as in *Annales de chimie et de physique*, 1820, vol. 14, pp. 417–425, and "Neuere elektro-magnetische Versuche," Schweigger's *Journal*, 1820, vol. 29, pp. 364–369).

[59] "On the Magnetic Phenomena Produced by Electricity; in a Letter from Sir H. Davy to W. H. Wollaston," *Philosophical Transactions*, 1821, vol. 111, pp. 7–19.

[60] Dominique Arago, "Extrait des séances de l'Académie Royale des Sciences," *Annales de chimie et de physique*, 1820, vol. 15, p. 80.

[61] Auguste de la Rive, "Notice sur quelques expériences électro-magnétiques," *Bibliothèque universelle, sciences et arts*, 1821, vol. 16, pp. 201–203.

[62] J. S. Schweigger, "Zusaetze zu Oersted's elektro-magnetische Versuchen," Schweigger's *Journal*, 1821, vol. 31, pp. 1–6.

[63] Ludwig Gilbert, "Untersuchungen ueber die Einwirkung des geschlossenen galvanisch-elektrischen Kreises auf die Magnetnadel," *Annalen der Physik*, 1820, vol. 66, pp. 331–391.

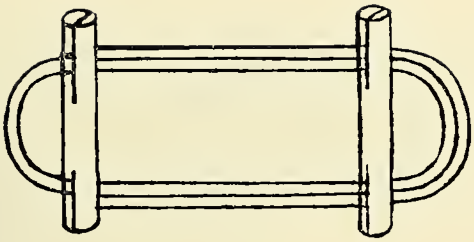

Figure 40.—Schweigger's multiplier. From Schweigger's *Journal für Chemie und Physik*, 1821, vol. 31, pl. 1 (after p. 114).

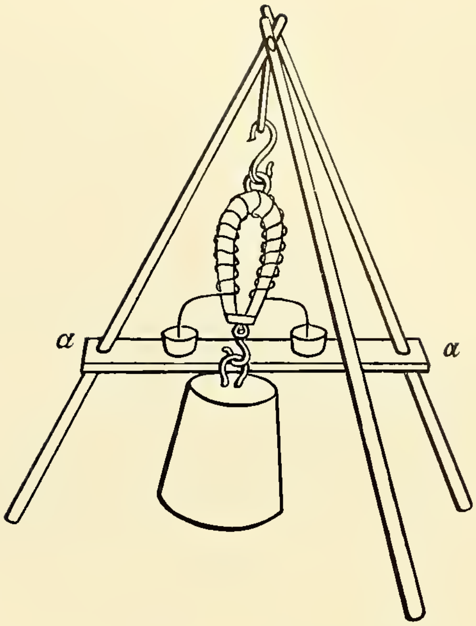

Figure 42.—Sturgeon's later electromagnet. From *Philosophical Magazine*, 1832, vol. 11, p. 201.

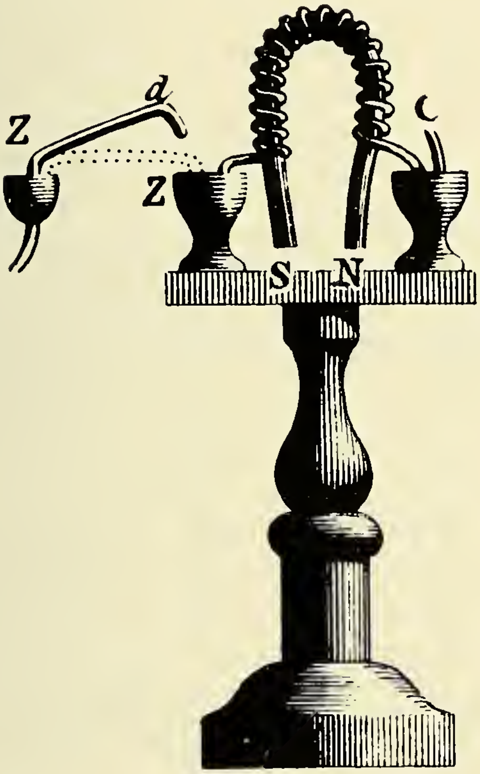

Figure 41.—Sturgeon's first electromagnet. From *Transactions of the Society for the Encouragement of the Arts, Manufactures and Commerce*, 1824, vol. 43, pl. 3.

In the early portion of his studies of the Oersted effect—which led to the foundation of the science of electrodynamics [64]—André-Marie Ampère pointed out that the combination of a wire and a magnetic needle was an indicator of an electric current and was in contrast to the (electrostatic) electrometer that detected an electrical tension or voltage. Although it was not the first device so called, Ampère proposed that this new combination of a wire and a magnetic needle be called a galvanometer.[65] Independently of Ampère and of one another, Schweigger and Poggendorff, repeating Oersted's experiments, found they could increase the effect of the current on the needle by rolling the wire into a coil and placing the needle inside. Schweigger called his coil a "Verstaerker" or multiplier (fig. 40),[66] while Poggendorff named his a "Condensator" or condenser.[67]

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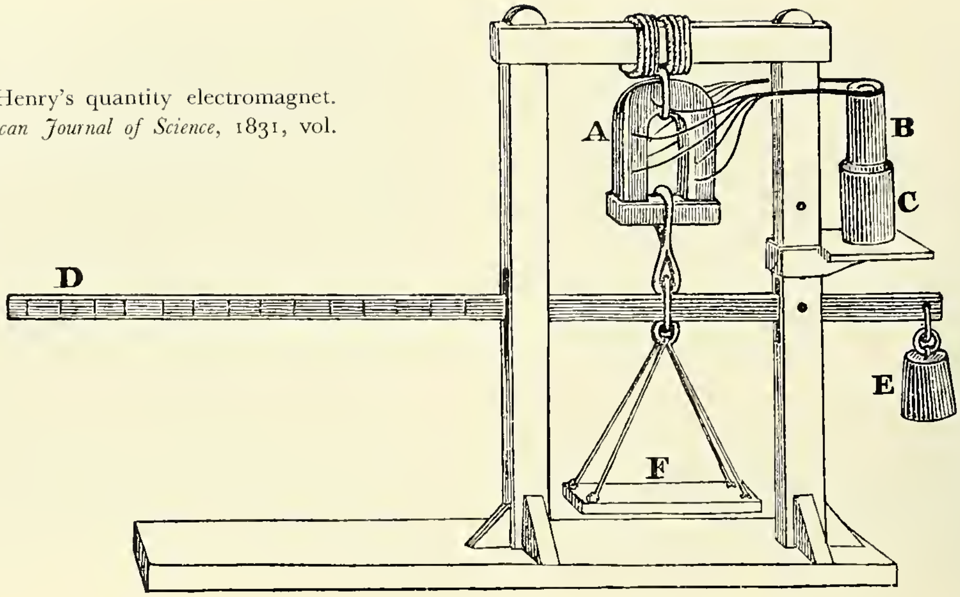
[64] A. M. Ampère, *Théorie des phénomènes électro-dynamiques, uniquement déduite de l'expérience*, Paris, 1826.

[65] *Journal de Paris*, September 18, 1800, vol. 8, no. 368. A. M. Ampère, "De l'action mutuelle de deux courants électriques," *Annales de chimie et de physique*, 1820, vol. 15, pp. 59–76.

[66] J. S. Schweigger, "Zusaetze zu Oersted's elektro-magnetische Versuchen," *Allgemeine Literatur-Zeitung*, 1820, no. 296, cols. 622–624; "Noch einige Worte über diese neuen elektromagnetischen Phänomene," Schweigger's *Journal*, 1821, vol. 31, pp. 35–41.

[67] J. C. Poggendorff, "Account of the New Galvano-Magnetic Condenser," *Edinburgh Philosophical Journal*, 1821, vol. 5, pp. 112–113.

Figure 43.—Henry's quantity electromagnet. From *American Journal of Science*, 1831, vol. 19, p. 408.



That an electric current not only will cause a magnet to move but can create a magnet was the discovery of Arago,[68] who found that a current-carrying conductor will attract iron filings, and that if wire is wound upon a glass tube, and a needle placed inside the tube, the needle will become a magnet when current is passed through the wire. Similar experiments performed by Arago together with Ampère led to the latter's circulating current theory of magnetism.[69] Instead of using a steel core in the form of a bar or cylinder, an English, self-taught physics teacher named William Sturgeon [70] used a horse-shoe-shaped soft iron core and obtained a much more concentrated magnetic field (fig. 41). In 1825 the *Society for the Encouragement of Arts, Manufacture, and Commerce* awarded Sturgeon a medal and a financial prize for this improvement on the electromagnet. By winding a bare wire on a varnished core so that the current passing through the wire would not short out, Sturgeon succeeded in producing an electromagnet that would support a weight of nine pounds when excited by a battery with 130 square inches of zinc (fig. 42). G. Moll [71] of the university at Utrecht, made a still larger electromagnet, weighing 26 pounds, that lifted 154 pounds when excited by a battery with 11 square feet of zinc.

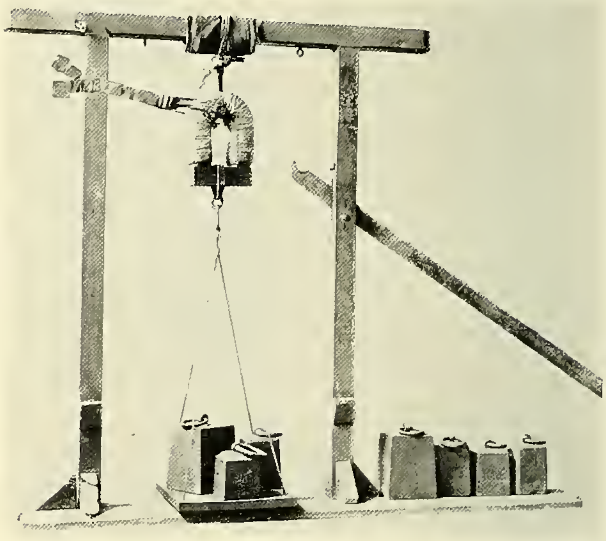


Figure 44.—Henry's "Yale" electromagnet. (*USNM 181343; Smithsonian photo 13346.*)

[68] Dominique Arago, "Expériences relatives à l'aimantation du fer et de l'acier par l'action du courant voltaïque," *Annales de chimie et de physique*, 1820, vol. 15, pp. 93–102.

[69] A. M. Ampère, "Suite du mémoire sur l'action mutuelle entre deux courants électriques, entre un courant électrique et un aiman ou le globe terrestre, et entre deux aimans," *Annales de chimie et de physique*, 1820, vol. 15, pp. 170–218.

[70] "Papers in Chemistry, No. 3: Improved Electro-Magnetic Apparatus," *Transactions of the Society for the Encouragement of Arts, Manufactures, and Commerce*, 1824, vol. 43, pp. 37–52.

[71] Gerard Moll, "Electromagnetic Experiments," *American Journal of Science*, 1830, vol. 19, pp. 329–337.

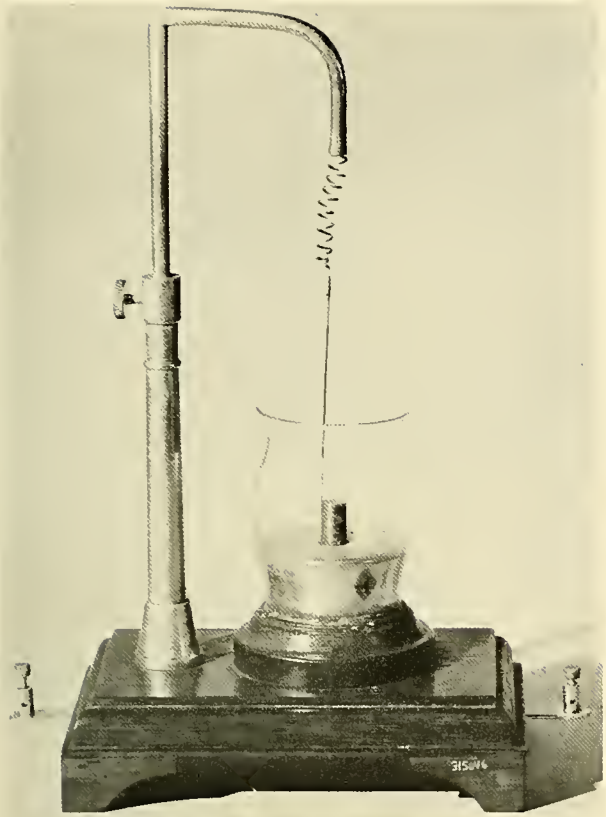


Figure 45.—A model of Faraday's circulating wire experiment. (*USNM 315046; Smithsonian photo 47048-C.*)

There were some experimenters in the United States, like James Dana and Rubens Peale, who were also exhibiting electromagnets about this time. A more serious investigator was Joseph Henry, then an instructor at Albany [New York] Academy but who was to become the first Secretary of the Smithsonian Institution. He was one of the first to try to obtain the optimum electromagnet from a given battery. Like Poggendorff,[72] Henry found that the pull of an electromagnet could be increased by adding more turns of wire but only up to a certain number of turns. After that number was reached, in order to increase the force, either the additional turns had to be connected in parallel with the turns already on the coil or a bat-

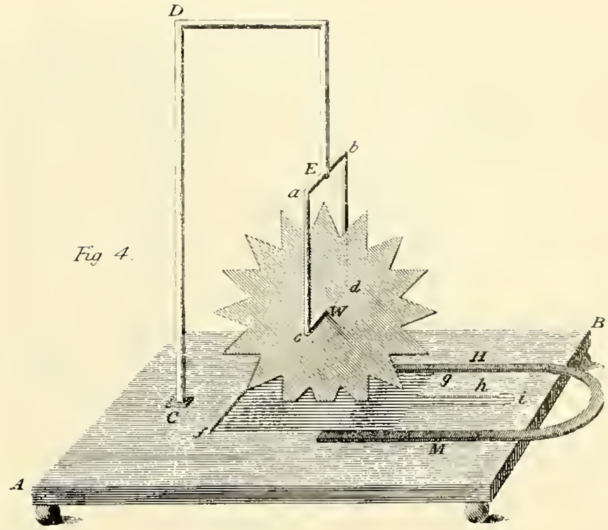


Figure 46.—Barlow's wheel. From *Philosophical Magazine*, 1822, vol. 59, pl. 4, fig. 4.

tery with more pairs of plates had to be utilized. These considerations led Henry to distinguish the kind of battery to which each of two kinds of electromagnets responded best: a quantity electromagnet of coils of wire in parallel that responded best to a quantity battery like Hare's calorimotor where the area of the plates is large, and an intensity electromagnet that responded best to an intensity battery like the Cruickshank trough where the number of plates is large. A quantity electromagnet and battery were the best to use for maximum lifting power; while to operate an electromagnet at the end of a long line of wire, an intensity battery at one end and an intensity electromagnet at the other were necessary. On the basis of such considerations, Henry constructed a quantity electromagnet (fig. 43) with a core weighing 21 pounds that used a cell with 72 square inches of zinc to lift 750 pounds.[73] When Professor Silliman of Yale heard of this feat, he requested Henry to make an even larger magnet, and in 1831 Henry constructed a magnet (fig. 44) weighing 59 pounds that lifted 2,000 pounds with a cell using 5

[72] J. C. Poggendorff, "Physisch-chemische Untersuchungen zur nähern Kenntnis des Magnetismus der voltaischen Säule," Oken's *Isis*, 1821, vol. 1, cols. 687–710.

[73] Joseph Henry, "On the Application of the Principle of the Galvanic Multiplier to Electro-Magnetic Apparatus, and also to the Development of Great Magnetic Power in Soft Iron, with a Small Galvanic Element," *American Journal of Science*, 1831, vol. 19, pp. 400–408.

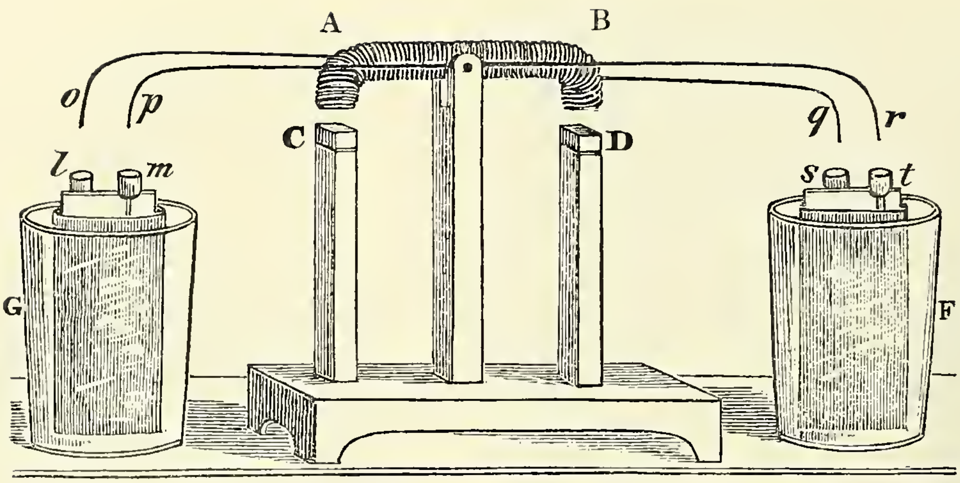


Figure 47.—Henry's electromagnetic motor. From *American Journal of Science*, 1831, vol. 20, p. 342.

square feet of zinc.[74] Two years later at Princeton Henry devised an electromagnet that held the astonishing weight of 3,600 pounds with a battery of 132 square inches of zinc that occupied only one cubic foot.[75]

In 1835 Professor Jacobi, apparently independent of Henry, began a more complete and systematic investigation of the electromagnet.[76] He completed this study in 1844.[77] Henry's distinction between quantity and intensity magnets was expressed again by Jacobi when he asserted that the greatest magnetic force was produced when the resistance of the coil equaled that of the voltaic battery. By the time of Jacobi's experimentation, several electric motors had been constructed, and some of his results were summarized in an article prescribing the proper design of a motor for a boat.[78] But we must turn back a little to examine some of the steps that led to the development of the motors of the 1840's.

ELECTRIC MOTORS

Once it was clear to Michael Faraday at the Royal Institution in London that a current-carrying conductor exerted a force on a magnetic needle, he sought some means of changing this static deflection into continuous rotation.[79] He finally succeeded in producing the circulation of a wire about a magnet and the circulation of a magnet about a wire (fig. 45). Peter Barlow[80] added some other devices to the ones Faraday invented (fig. 46), but both Faraday's and Barlow's apparatus were closer to "philosophical toys" than the machine that Joseph Henry created in 1831,[81] which is illustrated in figure 47.

Henry's apparatus was the first clear-cut instance of a motor capable of further mechanical development.

[74] Joseph Henry and Dr. Ten Eyck, "An Account of a Large Electro-Magnet, Made for the Laboratory of Yale College," *American Journal of Science*, 1831, vol. 20, pp. 201–203.

[75] "Deposition of Joseph Henry, in the Case of Morse *vs.* O'Reilly, taken at Boston, September, 1849," reprinted in *Annual Report of the . . . Smithsonian Institution . . . for the Year 1857*, 1858, pp. 109–110.

[76] M. H. Jacobi, "On the Application of Electro-Magnetism to the Moving of Machines," Sturgeon's *Annals of Electricity*, 1837, vol. 1, pp. 408–415, 419–444.

[77] M. H. Jacobi and E. Lenz, "Ueber die Anziehung der Elektromagnete," *Annalen der Physik*, 1839, vol. 47, pp. 401–418; "Ueber die Gesetze der Elektromagnete," *Annalen der Physik*, 1839, vol. 47, pp. 225–270; 1844, vol. 61, pp. 254–280, 448–466, and vol. 62, pp. 544–548.

[78] M. H. Jacobi, "Ueber die Principien der elektromagnetischen Maschinen," *Annalen der Physik*, 1840, vol. 51, pp. 358–372; "On the Principles of Electro-Magnetical Machines," Sturgeon's *Annals of Electricity*, 1841, vol. 6, pp. 152–159.

[79] Michael Faraday, "On Some New Electro-Magnetical Motions, and on the Theory of Magnetism," *Quarterly Journal of Science, Literature and Arts*, 1822, vol. 12, pp. 74–96.

[80] Peter Barlow, "A Curious Electro-Magnetic Experiment,' *Philosophical Magazine*, 1822, vol. 59, pp. 241–242.

[81] Joseph Henry, "On a Reciprocating Motion Produced by Magnetic Attraction and Repulsion," *American Journal of Science*, 1831, vol. 20, pp. 340–343.

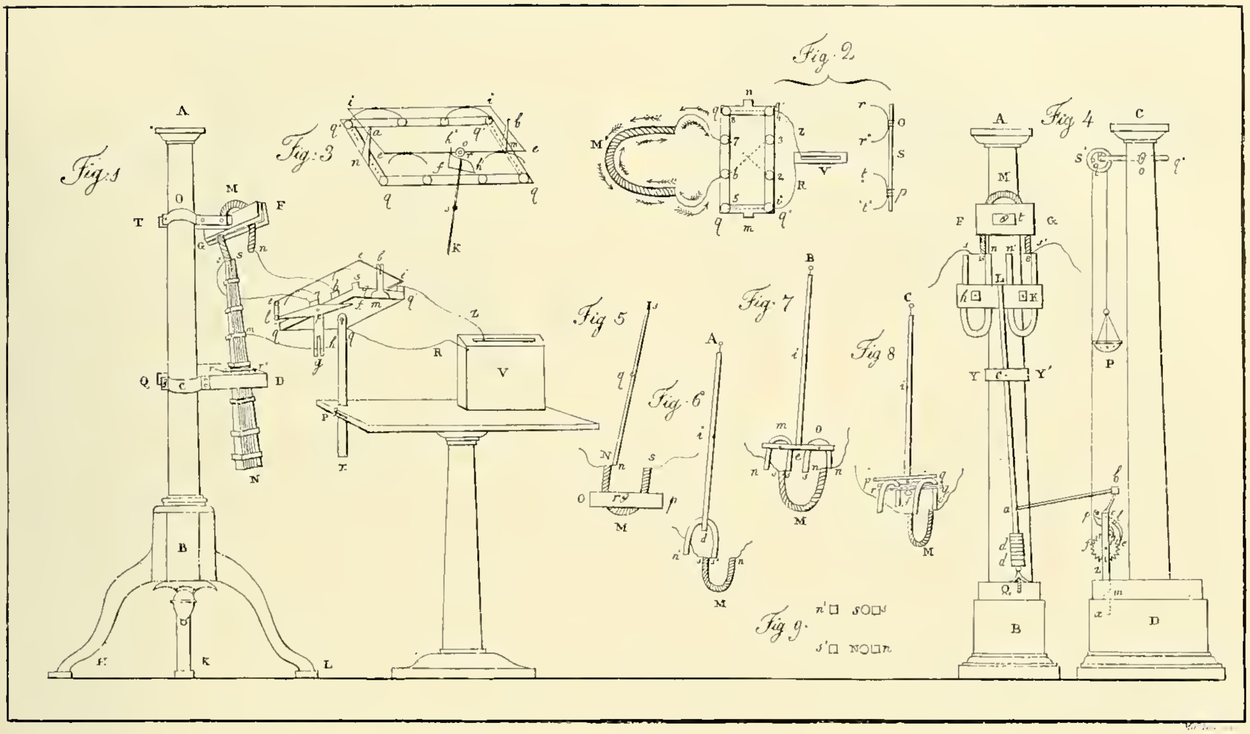


Figure 48.—Dal Negro's electromagnetic machine. From *Annali delle Scienze de Regno Lombardo-Veneto*, March 1834, pl. 4.

It had the essentials of a modern DC motor: a magnet to provide the field, an electromagnet as armature, and a commutator to apply the mechanical forces at the right time. The reciprocating motion of an armature, see-sawing up and down, made and broke contact during the motor's cycle so that the electromagnet pulled on the part of the armature farthest away. Salvatore dal Negro [82] of the university at Padua reported in 1834 on an invention that he had worked out in 1831 of a permanent magnet pendulum kept in oscillation by an electromagnet that changed its polarity by a commutator switch (fig. 48). He added a linkage device so that he could raise a weight with it and found it lifted 60 grams, 5 centimeters in one second. A similar pendulum-instrument was made in 1834 by J. D. Botto [83] in Turin.

Probably the first man to produce the rotary motion of an electromagnet was an English experimenter, Rev. William Ritchie,[84] in 1833. At the end of an article on the attractive force of an electromagnet, he described how an electromagnet could be made to spin and how he was able to set the magnet in sufficiently rapid rotation to raise several ounces over a pulley (fig. 49). About the same time, Dr. T. Edmundson of Baltimore, Maryland, devised a kind of magnetic paddlewheel motor [85] (fig. 50).

During the period of the 1820's and early 1830's, the most successful experimenters with electromagnetism—men like Faraday, Barlow, Sturgeon, Henry, and Ritchie—used chemical cells like Hare's calorimotor. The calorimotor was one of the best cells available, but even so it was bulky in volume and the current it supplied rapidly decreased because of

[82] Salvatore dal Negro, "Nuova Macchina élettro-magnetica immaginata dall'Abate Salvatore dal Negro," *Annali delle scienze de regno Lombardo-Veneto*, March 1834, pp. 67–80.

[83] J. D. Botto, "Note sur l'application de l'électro-magnétism à la mécanique," *Bibliothèque universelle, sciences et arts*, 1834, vol. 56, pp. 312–316.

[84] W. Ritchie, "Experimental Researches in Electro-Magnetism and Magneto-Electricity," *Philosophical Transactions*, 1833, vol. 123, pp. 313–321.

[85] T. Edmondson, "The Rotating Armatures," *American Journal of Science*, 1834, vol. 26, pp. 205–206.

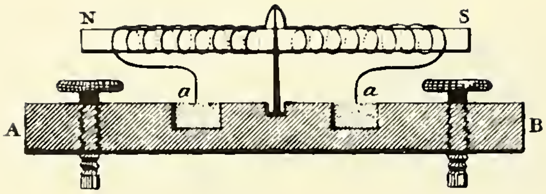


Figure 49.—Ritchie's motor. From *Philosophical Transactions of the Royal Society of London,* 1833, vol. 123, p. 316, pl. 7.

polarization and secondary action, as was true of all its predecessors.

Beginning in the middle 1830's chemical cells were being invented that avoided the polarization and local action of earlier cells. These new cells were good sources of current, and they could produce this current over a longer period of time than could the earlier cells. In addition scientists understood better how to build a strong electromagnet, and how to turn its force on and off by a commutator. It was no accident that electric motors began to seem practical to inventors in the 1830's, for the main elements of a motor were present; it was not long before inventors began to assemble these elements into a device that could be used to drive machinery.

In 1836 William Sturgeon [86] asserted that he had constructed an electric motor in the fall of 1832 (fig. 51), had demonstrated it in March 1833, and had later used it to run models of machinery. Francis Watkins [87] made electric motors (fig. 52) in 1835 that could also be used to drive mechanical models.

In May 1834 M. H. Jacobi [88] built an electric motor (fig. 53) that could lift 10 to 12 pounds at a speed of one foot per second when tested by a Prony brake. Further details on this motor, showing how much zinc was needed to produce a given amount of mechanical work, appeared the following year.[89] Jacobi claimed that a half-pound of zinc would deliver the "demi-force d'un homme" for 8 hours.

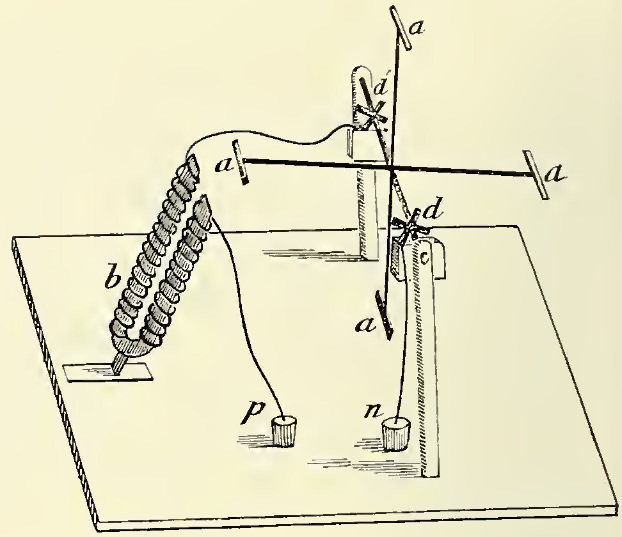


Figure 50.—Edmondson's motor. From *American Journal of Science,* 1834, vol. 26, p. 205.

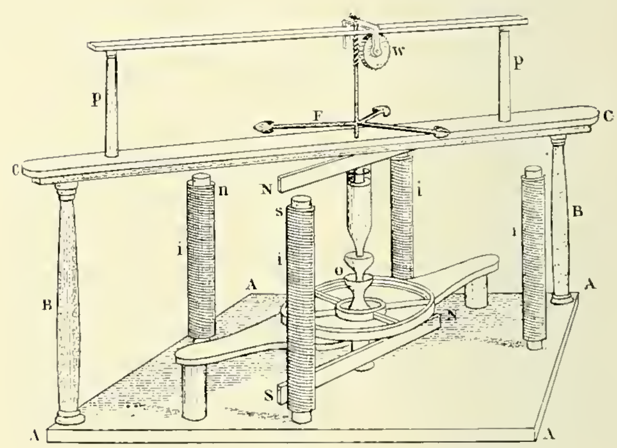


Figure 51.—Sturgeon's motor. From Sturgeon's *Annals of Electricity,* 1837, vol. 1, pl. 2, fig. 17.

In a petition in May 1837 to the Russian czar, Jacobi expressed his high hopes for a well-supplied workshop and 8,000 rubles for 8 years in order to "cover the Neva rather than the Thames or Tiber with magnetic boats." [90] By 1838 Jacobi was able

[86] William Sturgeon, "Description of an Electro-Magnetic Engine for Turning Machinery," Sturgeon's *Annals of Electricity,* 1836, vol. 1, pp. 75–78.

[87] Francis Watkins, "On Magneto-Electric Induction," *Philosophical Magazine,* 1835, vol. 7, pp. 107–113; "On Electro-Magnetic Motive Machines," *Philosophical Magazine,* ser. 3, 1838, vol. 12, pp. 190–196.

[88] M. H. Jacobi in *L'Institut,* 1834, vol. 2, pp. 394–395.

[89] Jacobi, *op. cit.* (footnote 76).

[90] D. V. Efremov, *The Electromotor in its Historical Development,* Moscow and Leningrad, 1936, pp. 230–247. (In Russian.)

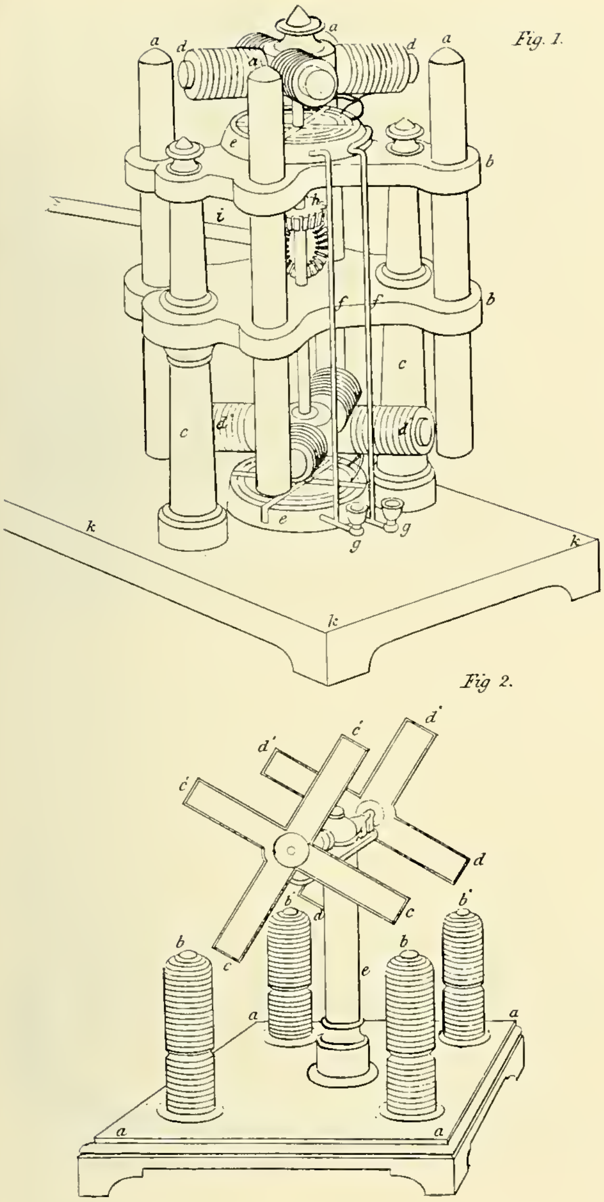


Figure 52.—Watkins' motors. From *Philosophical Magazine*, 1838, vol. 12, pl. 4.

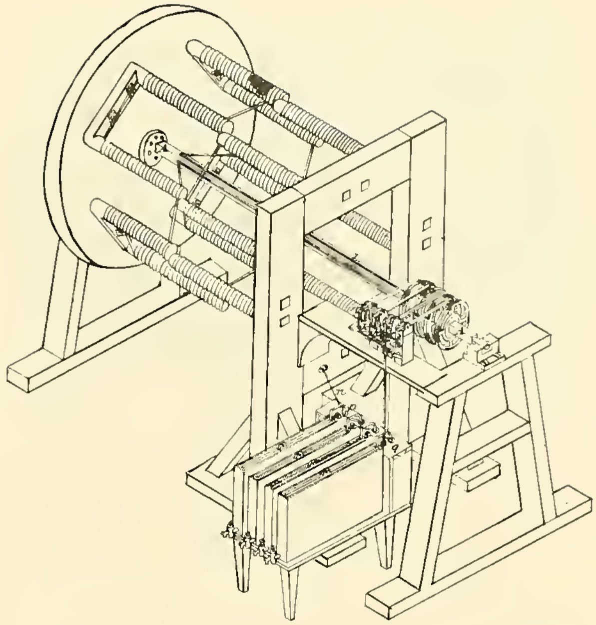


Figure 53.—Jacobi's motor. From Sturgeon's *Annals of Electricity*, 1837, vol. 1, pl. 13.

to use his motor to drive a boat 28 feet long, 7½ feet wide and drawing 2¾ feet of water.[91] Carrying a dozen or so officials of the Russian government, this boat moved at the speed of 1½ miles an hour on the Neva river. The following year, using the same motor, Jacobi found he could double the speed by using 64 Grove cells with the same electrode area. One suspects the fumes from the 64 cells probably contributed as much to the dropping of the project as did the breakdowns of the motor.

The first inventor to build an electric motor able to perform useful work was probably Thomas Davenport, a blacksmith of Brandon, Vermont.[92] In 1833 Davenport was so fascinated by the operation of one of Henry's electromagnets that he bought one. By July 1834 he had worked out a motor with a 7-inch flywheel that rotated at a speed of 30 rpm. Using a shunt-wound motor for drive, Davenport built a motor on rails that is usually called his miniature "train" (fig. 54). He had applied for a patent on his electric motor in 1835, but the fire at the Patent Office in Washington destroyed his application

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[91] Jacobi, *op. cit.* (footnote 52).

[92] Franklin L. Pope, "The Inventors of the Electric Motor," *Electrical Engineer*, 1891, vol. 11, pp. 1–5, 33–39, 65–71, 93–98, 125–130; Walter R. Davenport, *Biography of Thomas Davenport*, Montpelier, Vermont, 1929; Mary Somerville, *Electromagnetism—History of Davenport's Invention of the Application of E'ectromagnetism to Machinery*, New York, 1837.

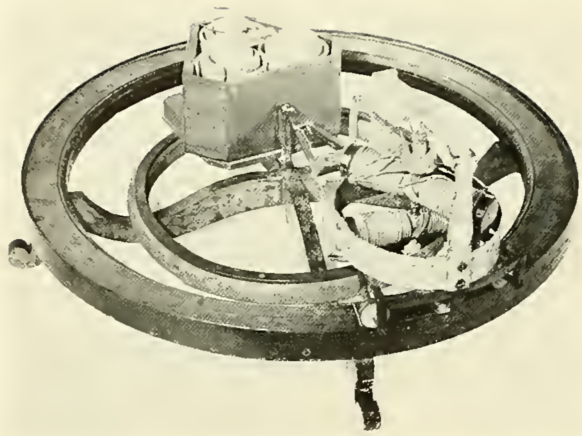

Figure 54.—Davenport's model of an electric "train." The circular track is 4 feet in diameter. (*USNM 181825; Smithsonian photo 38403.*)

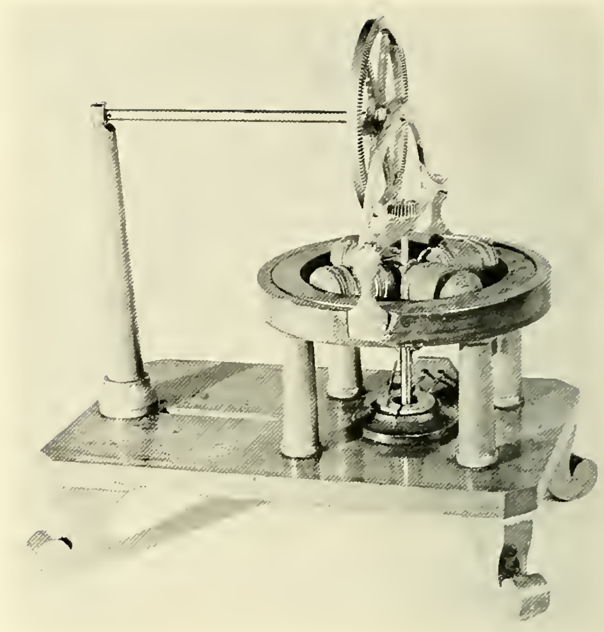

Figure 55.—Patent Office model of Davenport's electric motor. (*USNM 252644; Smithsonian photo 44978.*)

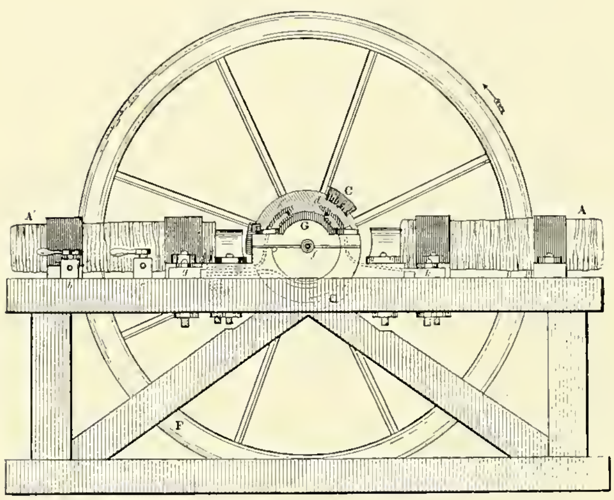

Figure 56.—Davidson's motor. From *Electrical World*, 1890, vol. 16, p. 277, fig. 2.

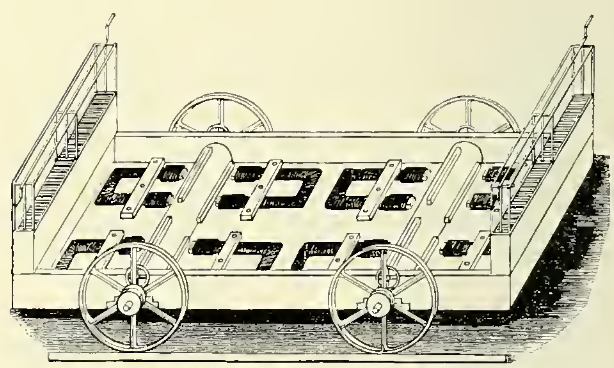

Figure 57.—Davidson's electric locomotive. From T. du Moncel, *Electricity as a Motive Power*, London, 1883, fig. 32.

and he had to apply again in February 1837[93] (fig. 55). By August 1837 he had developed a motor with a 6-pound rotor, about half a foot across, that rotated at a speed of 1,000 rpm and that could raise a 200-pound weight at a speed of 1 foot per minute when driven by three cells. Later in the year, he used this new machine to run a drill and turn a piece of hard wood 3 inches in diameter on his lathe.[94] In an exhibition in

[93] Thomas Davenport, "Specification of a Patent for the Application of Electro Magnetism to the Propelling of Machinery," *Journal of the Franklin Institute*, 1837, vol. 20, pp. 340–343. U.S. Patent 132, February 25, 1837.

[94] "Notice of the Electro-Magnetic Machine of Mr. Thomas Davenport of Brandon, Near Rutland, Vermont," *American Journal of Science*, 1837, vol. 32, appendix, pp. 1–8; also *Mechanics' Magazine*, London, 1837, vol. 27, pp. 159, 204–207, 404–405, and letter from Thomas Davenport to editor, *American Journal of Science*, 1838, vol. 33, appendix, pp. 1–2.

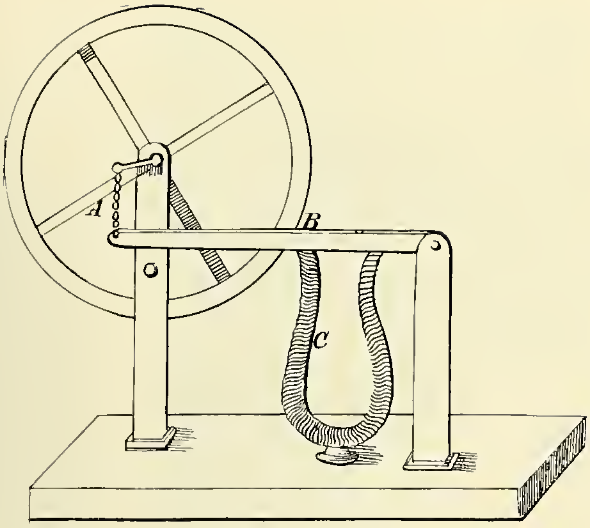

Figure 58.—Clarke's motor. From Sturgeon's *Annals of Electricity*, 1840, vol. 5, pl. 1, fig. 3.

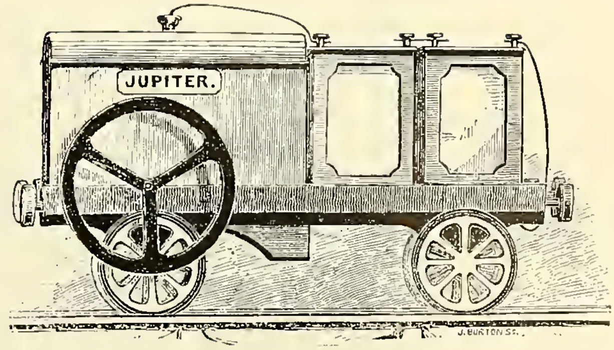

Figure 59.—Clarke's electric locomotive. From Sturgeon's *Annals of Electricity*, 1840, vol. 5, p. 304.

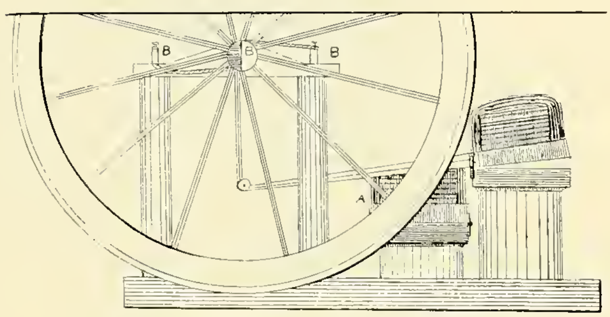

Figure 60.—Wright's motor. From Sturgeon's *Annals of Electricity*, 1840, vol. 5, pl. 3, fig. 4.

London in August 1838, one of Davenport's motors drove a small electric train of several carriages with a total weight of 70 to 80 pounds at a speed of 3 miles per hour.[95] Davenport tried to use his rotating motor to drive a Napier printing press that printed his paper "The Electro-Magnet," but the press required an engine from 1 to 2 horsepower, and he did not succeed in building such a motor until 1840.[96] Success came to Davenport with his development of a reciprocating engine based on a "sucking coil" that he had begun working on in 1838. Davenport built over 100 motors in his lifetime, but lack of financial backing and his inability to obtain an inexpensive source of power defeated him.

By the early 1840's there were a number of inventors of electric motors. In 1839 Robert Davidson of Edinburgh constructed an electric motor that had enough power to turn articles on a lathe or to drive a small carriage (fig. 56). Three years later, Davidson's motor could drive a carriage weighing about 6 tons for a mile and a half at a speed of 4 miles per hour.[97] A drawing of this 1842 motor is shown in figure 57. In 1840 Uriah Clarke[98] devised a reciprocating engine (fig. 58) and then applied it to a 100-pound miniature railway (fig. 59). Thomas Wright[99] reported on a reciprocating engine (fig. 60) that Clarke promptly criticized as impractical. William Taylor patented an electric motor[100] (fig. 61) in 1840. James Joule[101] worked on several different models of electric motors,

[95] *Mechanics' Magazine*, London, 1838, vol. 28, pp. 321–323; vol. 29, pp. 95–96, 115, 166–168, 170–172.

[96] *Ibid.*, 1840, vol. 32, pp. 407–408.

[97] *Ibid.*, 1840, vol. 33, p. 92; "Electro-Magnetic Locomotive Carriage," Sturgeon's *Annals of Electricity*, 1842, vol. 9, 234–235; "The Earliest Electrical Railway," *Electrical World*, 1890, vol. 16, pp. 276–277.

[98] Uriah Clarke, "Description of an Electro-Magnetic Engine," Sturgeon's *Annals of Electricity*, 1840, vol. 5, pp. 33–34; "Description of an Electro-Magnetic Locomotive Carriage," Sturgeon's *Annals of Electricity*, 1840, vol. 5, pp. 304–305.

[99] Thomas Wright, "On a New Electro-Magnetic Engine," Sturgeon's *Annals of Electricity*, 1840, vol. 5, pp. 108–110.

[100] British Patent 8255, November 2, 1839.

[101] James Joule, "Description of an Electro-Magnetic Engine," Sturgeon's *Annals of Electricity*, 1838, vol. 2, pp. 122–123; 1839, vol. 3, pp. 437–439; 1840, vol. 4, pp. 203–205.

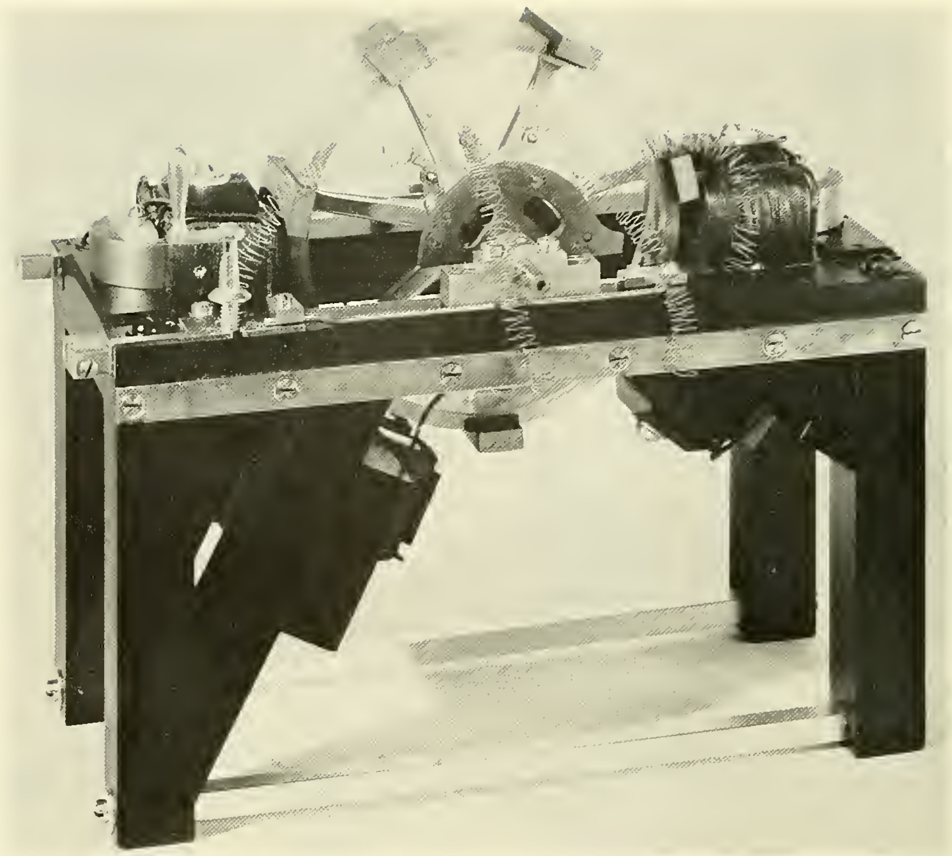

Figure 61.—Taylor's motor. (*USNM 181992; Smithsonian photo 47048.*)

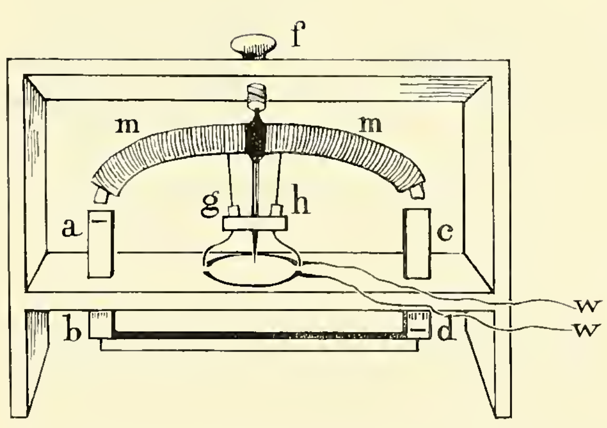

Figure 62.—Joule's rotating motor. From Sturgeon's *Annals of Electricity*, 1839, vol. 3, pl. 13, fig. 1.

including the one shown in figure 62. He devised another kind of motor (fig. 63) in 1842. In the same year, P. Elias, of Haarlem, invented a motor with a ring-type armature [102] (fig. 64).

There were other inventors of electric motors in the the United States. G. Q. Colton,[103] a traveling dentist fresh out of medical college, while demonstrating some wonders of science like laughing gas and the Morse telegraph, made an electric motor that he added to his show. In 1847 Colton placed a reciprocating motor, 14 inches long by 5 inches wide, on a track, and sent power from four Grove cells through the track. This invention (fig. 65) was widely exhib-

[102] *La Lumière électrique*, 1882, vol. 7, pp. 13–14.

[103] *Scientific American*, September 25, 1847, vol. 3, p. 4. T. C. Martin, "The Electric Railway Work of Dr. Colton in 1847—The First Use of Track as Circuit," *Electrical Engineer*, 1893, vol. 16, pp. 49–51.

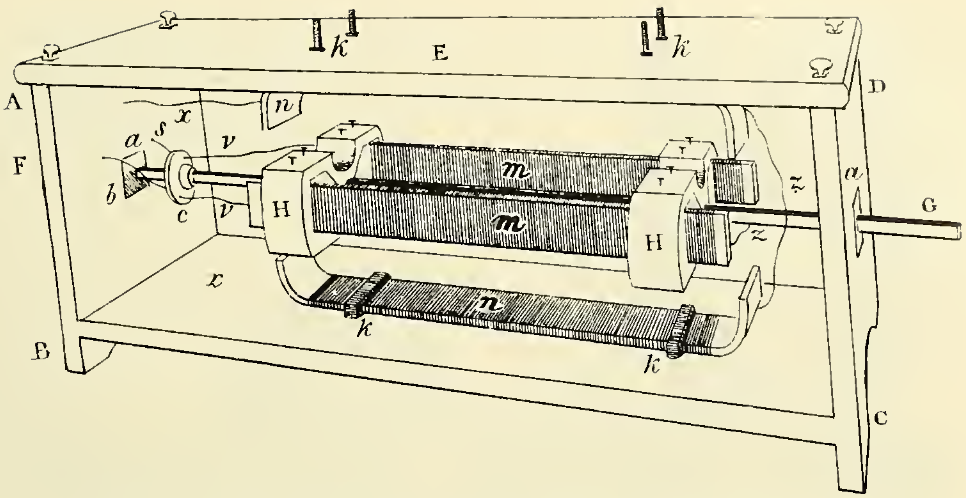

Figure 63.—Joule's motor of 1842. From Sturgeon's *Annals of Electricity*, 1840, vol. 4, pl. 5, fig. 3.

ited and reported throughout the northern and western United States. In 1850 Thomas Hall, one of the assistants to Daniel Davis, a Boston instrument-maker, demonstrated a miniature electric railway in Boston. T. C. Avery patented an electric motor[104] in 1851.

One of the most prolific of these early American inventors was Charles G. Page,[105] many of whose inventions (figs. 66, 67) later appeared in the popular catalogs of Daniel Davis. Page began his work on electric motors in 1837, and by the following year had one that could be used by Davis to power a drill.[106] Shortly thereafter Page moved to Washington, D.C., where he became a Patent Office examiner. After obtaining a $20,000 appropriation from the Government in 1849 he was able to build two motors that were definitely out of the class of "philosophical toys." By the following year his reciprocating motor (fig. 68) could deliver one horsepower, and a short time later he was able to quadruple its output. He estimated the cost of driving the lathe and saw of his shop with this 4-horsepower engine as 20 cents per horsepower-day.[107] In 1851 two of Page's motors drove a 10-ton locomotive at a speed of 10 miles per

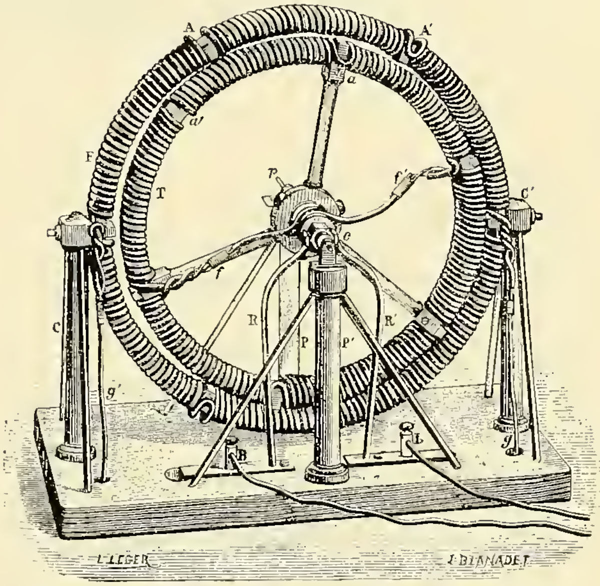

Figure 64.—Elias' ring armature motor. From *La Lumière électrique*, 1882, vol. 7, p. 14, fig. 13.

[104] U.S. Patent 7950, February 25, 1851. The Patent Office model is in the Smithsonian Institution (USNM 308563).

[105] "Charles Grafton Page," *American Journal of Science*, 1869, vol. 48, pp. 1–17.

[106] Charles G. Page, "Experiments in Electro-Magnetism," *American Journal of Science*, 1838, vol. 33, pp. 118–120; "Electro-Magnetic Apparatus and Experiments," *American Journal of Science*, 1838, vol. 33, pp. 190–192; "Magneto-Electric and Electro-Magnetic Apparatus and Experiments," *American Journal of Science*, 1839, vol. 35, pp. 252–268.

[107] Charles G. Page, "On Electro-Magnetism as a Moving Power," *American Journal of Science*, 1850, vol. 10, pp. 343–349, 473–476.

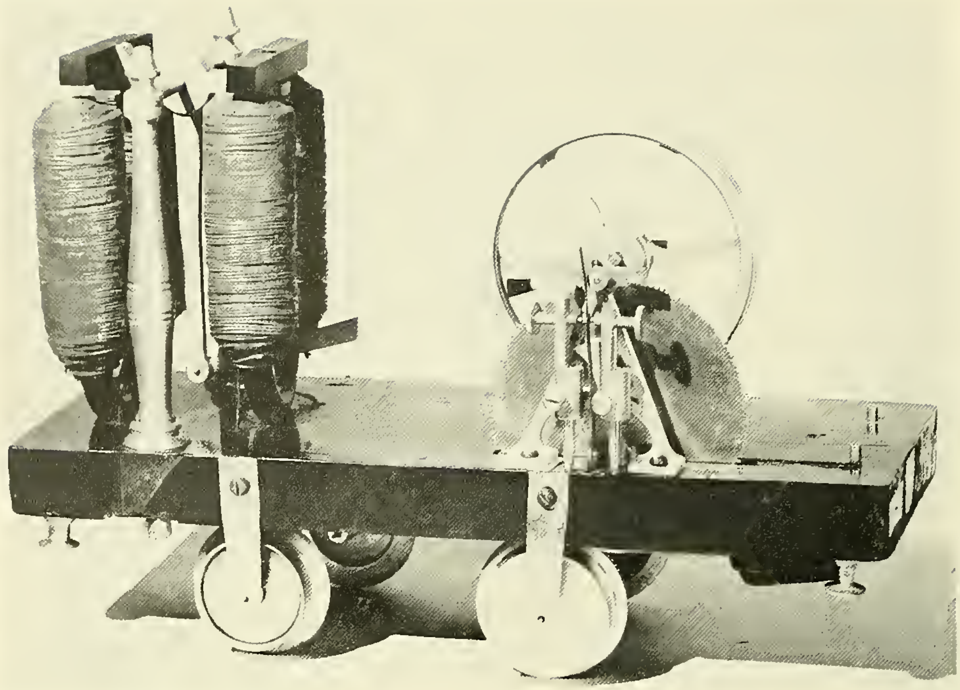

Figure 65.—Colton's electric locomotive. (*USNM 181577; Smithsonian photo 47048–B.*)

hour. A few months later, his motors had reached an estimated 8 to 20 horsepower, and on a 39-minute trip from Washington to Bladensburg had driven a locomotive at a top speed of 19 miles per hour.[108] However, the trip was so rough the diaphragms of the 50 Grove cells—required for each motor—and the insulation in the motors broke down. Page's funds were exhausted by then, and he made no further experiments.

Another of these successful early inventors was Moses G. Farmer of Dover, New Hampshire. Farmer devised an electric motor in 1846 that in its first public exhibition in July 1847 drove an electric train (fig. 70) of two cars on an 18-inch-gauge track.[109] Farmer had other exhibitions in New England later in the year; but his exhibitions were not financially successful, so he turned to the field of telegraphy.

By midcentury the general public was becoming increasingly aware of the possibilities of electrical power. Part of the increase in public attention resulted from the awarding of prizes for the invention and use of electric motors. Beginning in 1844 the French instrument-maker G. Froment constructed many motors (such as the one shown in fig. 69). Napoleon III awarded him the Volta prize in 1857 for having a shop completely run by electric motors.[110] Søren Hjorth, of Denmark, developed a motor (fig. 71) that was shown at the Great Exhibition of 1851 in London, where it won considerable attention as well as a prize.

By this time two basic forms of the electric motor had been developed. One of the basic forms was a reciprocating engine, where an armature was pulled into a solenoid, as in Page's motor, or an armature hinged at one end was pulled down by an electromagnet, as in Clarke's motor. Linkages changed the linear motion to a rotary one. The other basic form

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[108] Walter K. Johnson, "Report on Professor Page's Electro-Magnetic Locomotive," *American Journal of Science*, 1851, vol. 11, pp. 473–476; "Professor Page's Electric Engine," *Scientific American*, 1854, vol. 9, p. 394. Page patented his electric motor (U.S. Patent 10480) on January 31, 1854.

[109] *Electricity and Electrical Engineering*, 1893, vol. 4, p. 279.

[110] *Cosmos*, May 8, 1857, vol. 10, pp. 495–497; *Les Mondes*, May 7, 1863, vol. 1, pp. 337–338.

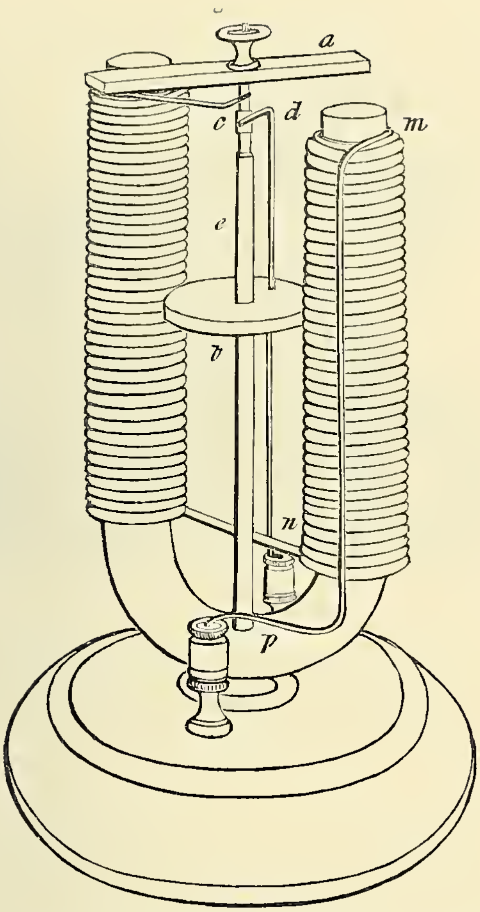


Figure 66.—Page's rotating motor. From *American Journal of Science,* 1838, vol. 35, p. 262.

was a paddle wheel, where an armature was kept in constant motion by a commutator switching on a field to tease the armature ahead at the right time. The engines of Ritchie, Jacobi, Davenport, Davidson, and Froment were of this second form. After mid-century there was a further proliferation of electric motors, but no new basic types were introduced until the advent of AC power.

In spite of the sanguine hopes of many of the early inventors, most scientists and engineers could not see any advantage in the use of electric power over that of steam. The greatest difficulty in the use of electricity lay in the relatively high cost of production of electrical power in comparison with that of steam. Instead of consuming coal in a chemical reaction that produced heat and the expansion of water, one dissolved a metal in an acid in a chemical reaction

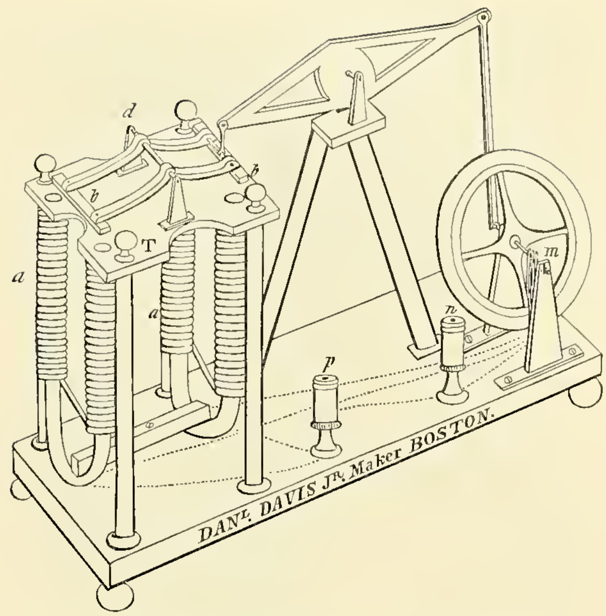


Figure 67.—Page's reciprocating motor. From *American Journal of Science,* 1838, vol. 35, p. 264.

that produced an electrical current. Metals and acids were much more expensive than coal and water.

A few engineers and scientists calculated just how much more expensive it was to produce an electrical current than it was to produce steam. In 1846 Scoresby and Joule [111] estimated that an electric motor could raise 80 pounds a distance of 1 foot for each grain of zinc consumed, while the best Cornish steam engine would raise 143 pounds the same distance for each grain of coal that was burned. Page had estimated the cost of his 1850 motor as greater than that of the cheaper steam engines but less than that of the highest priced ones.[112] Robert Hunt made an even more adverse estimate than Scoresby and Joule had made when he calculated in 1850 that electrical power was 25 times more expensive than steam power.[113] Obviously the electric motor could not

[111] William Scoresby and James Joule, "Experiments and Observations on the Mechanical Powers of Electro-Magnetism, Steam and Horses," *Philosophical Magazine,* 1846, vol. 28, pp. 448–455; also *Philosophical Magazine,* 1850, vol. 36, pp. 550–552.

[112] Charles Page, *op. cit.* (footnote 107).

[113] Robert Hunt, "On the Application of Electro-Magnetism as a Motive Power," *Journal of the Franklin Institute,* 1850, vol. 20, pp. 334–336.

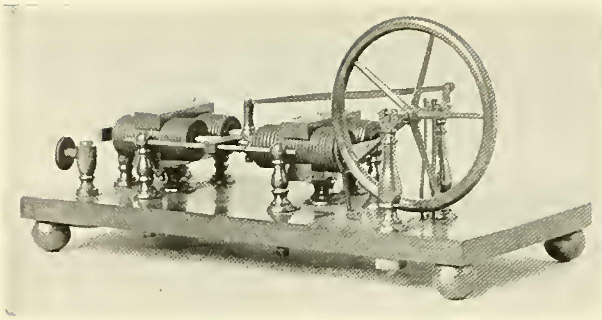


Figure 68.—Patent Office model of Page's reciprocating motor. (*USNM 252672; Smithsonian photo 29677.*)

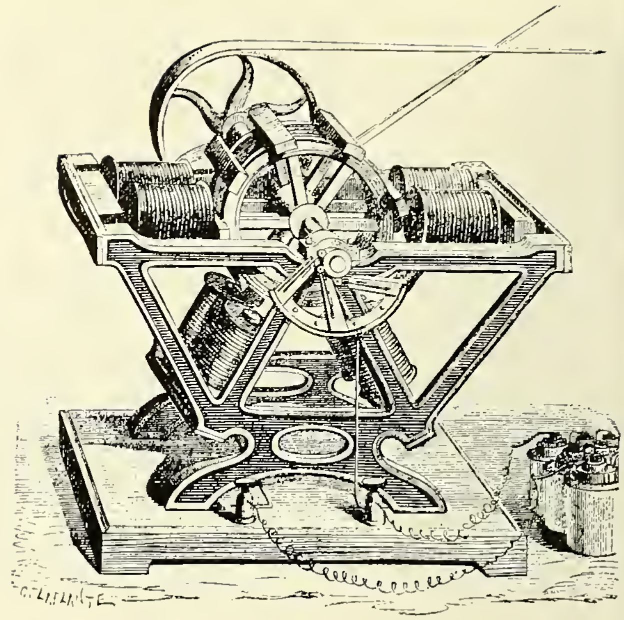


Figure 69.—One of Froment's motors. From T. du Moncel, *Electricity as a Motive Power*, London, 1883, fig. 35.

compete with steam until some cheaper means of producing electrical current could be found.

Another very important deterrent to the use of electrical power was the problem of distributing electrical current. Although by midcentury one could signal over long distances, power could be transmitted efficiently only within an area the size of a large room. Until some better means of distributing electricity was found, inventors had to use very bulky containers full of corrosive liquids directly at the place where the power was consumed.

The problems of the production and distribution of power were not solved until after the invention of the dynamo and the transformer. Moreover, on the eve of the last two decades of the 19th century—decades that were to see the explosive development of electrical technology—Théodose du Moncel was expressing the opinion of most scientists and engineers when he warned against the "pompous announcements of certain constructors and certain journals"

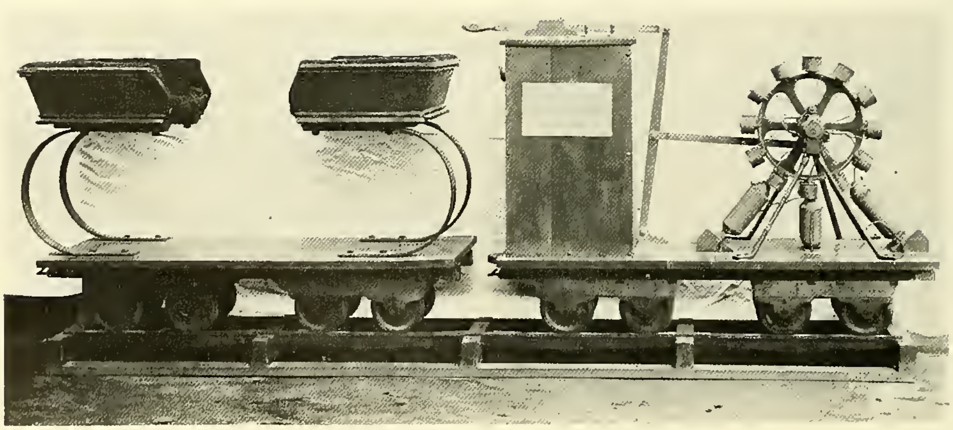
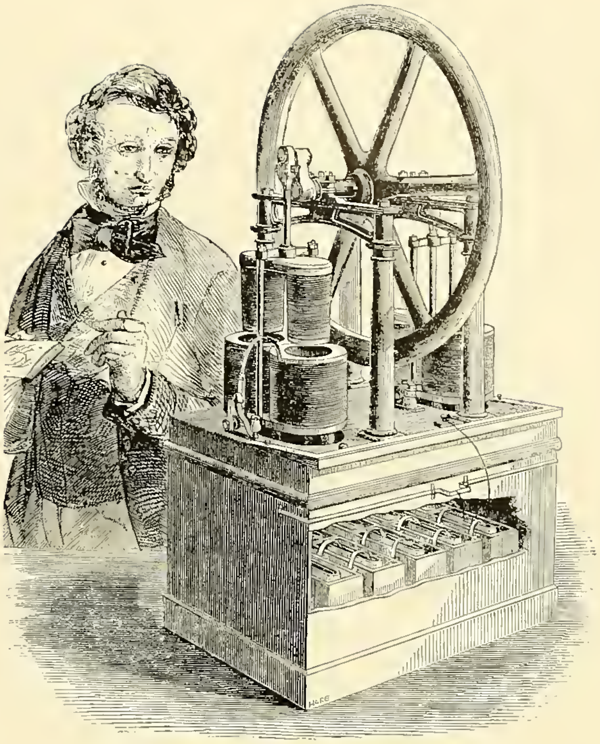


Figure 70.—Reproduction model of Farmer's electric train. The locomotive is about 4 feet in length. (*USNM 181348; Smithsonian photo 14588.*)

Figure 71.—Hjorth's motor. From *Illustrated London News,* May 12, 1849, vol. 14, p. 309.



and asserted that "what is certain until the present time, is that no electric motor has reached one horsepower in magnitude." [114] However, Du Moncel was not pessimistic, for he saw in the dynamo that had recently been invented a device that might be converted into a commercially successful motor. How this development occurred will be discussed in a subsequent article of this series.

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[114] Théodose du Moncel, *Exposé des applications de l'électricité* ed. 3, Paris, 1878, vol. 5, p. 343.

Contributions from

The Museum of History and Technology

Paper 30

The Development of Electrical Technology in the 19th Century

III. The Early Arc Light and Generator

W. James King

THE DEVELOPMENT OF ELECTRICAL TECHNOLOGY IN THE 19th CENTURY:

3. The Early Arc Light and Generator

by W. James King

In 1843 Louis Deleuil showed that he could light the Place de la Concorde in Paris with electricity by using Bunsen cells and charcoal electrodes. Only a few years later the first commercial successes of the electric light occurred when Staite, of England, and Duboscq, of France, used their arc lights in theatrical productions.

After Faraday discovered the induction of electric current he devised a magnetoelectric generator, in 1831. However, the practical development of the generator was slow. It was only after the dynamo principle of self-excitation had been applied to generators, in the 1860's, and after Jablochkoff showed that many arc lights could be connected to a single generator, in the 1870's, that the electric light became economically feasible.

American developments will be discussed in a subsequent article.

THE AUTHOR: *W. James King—formerly curator of electricity, United States National Museum, Smithsonian Institution—is associated with the American Institute of Physics.*

THE first commercially successful application of electricity in the 19th century—to electroplating—created a demand for electrical power that could be only partially satisfied by the expensive method of dissolving metals in acids. The second application of electricity, to communications, found adequate sources of power in such chemical cells, but not the next phase in the development of electrical technology. Even more so than in electroplating, the attempts to produce light by electricity required much sturdier and more potent sources of electrical current than chemical cells.

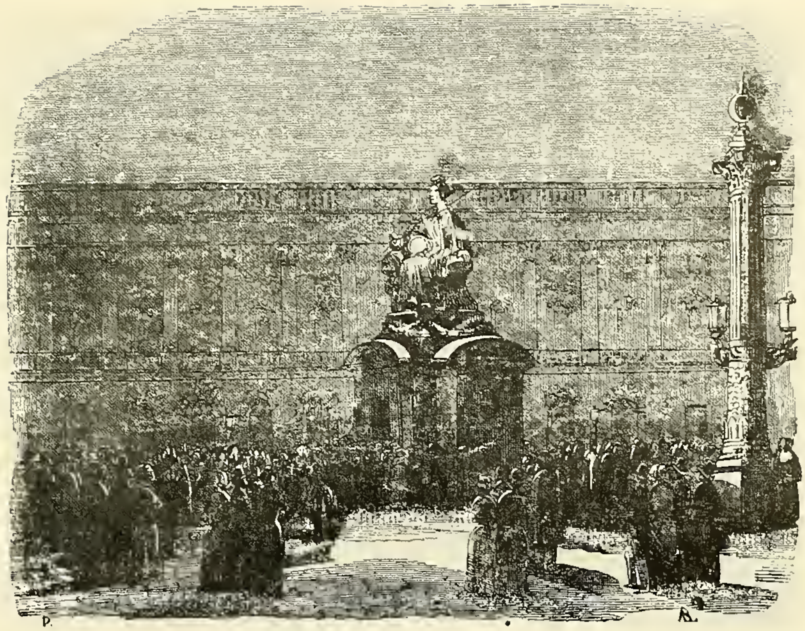

Figure 1.—Deleuil demonstrates his electric light on the Place de la Concorde in Paris, October 20, 1843. From *L'Illustration*, 1843, vol. 2, p. 132.

Although electric illumination could become commercially practical only after mechanical energy had been substituted for chemical energy in the transformation that produced electrical energy, still, the initial advances in the field of electrical light were made with power from chemical cells. By mid-century there were indications that such an application of electricity might be commercially profitable but it was clear that other sources of power had to be found.

Shortly after the voltaic cell was devised, it was found that the current from the cell could produce a number of strange new physical and chemical effects. Attempts to determine the different effects of voltaic electricity included studying the sparks obtained between various materials, which, Humphrey Davy found, became much brighter with charcoal than with metals. Using a battery of 500 double plates at the Royal Society, Davy announced in December 1808 that a glowing arc almost an inch long could be obtained in this manner. By using a 2,000-plate battery at the Royal Institution the following year, he obtained an arc three inches long.[1] In spite of its brilliance, no efforts were made to use the newly found "electric light" because of its impermanence.

At the same time, another source of electric light had been suggested in the incandescent glow of fine metallic wires when heavy currents go through them. But the same problems were found to occur with incandescent filaments as with arcs from charcoal. Up to the 1840's, any attempt to use the galvanic current as a practical source of light was futile because of the too-rapid consumption of the charcoal or of the incandescent wire and because the current from the chemical battery lasted for only a short time. An additional difficulty in using charcoal in an arc was that of maintaining the correct separation of the electrodes in the face of rapid and irregular burning.

The 19th century saw much experimentation and progress in public illumination, and after the invention of the Bunsen and the Grove cells experimenters began to examine seriously the possibility of using the new agency for this purpose. Some of the first successful attempts were made by the Parisian instru-

[1] Humphrey Davy, "An Account of Some Experiments on Galvanic Electricity, Made in the Theater of the Royal Institution," *Journal of the Royal Institution of Great Britain*, 1802, vol. 1, pp. 165–167; "An Account of Some New Analytical Researches on the Nature of Certain Bodies, Particularly the Alkalies, Phosphorus, Sulphur, Carbonaceous Matter, and the Acids Hitherto Undecompounded; with Some General Observations on Chemical Theory," *Philosophical Transactions*, 1809, vol. 99, pp. 39–104. *Philosophical Magazine*, 1810, vol. 35, p. 463.

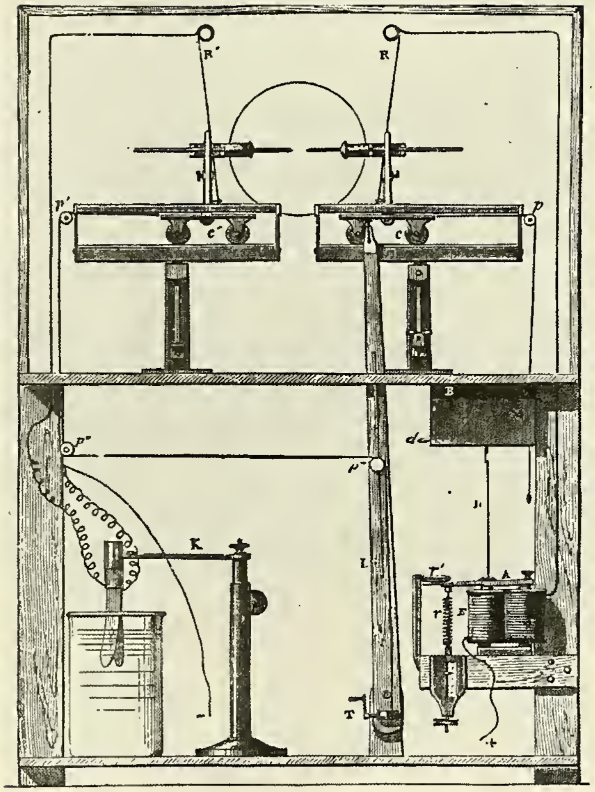

Figure 2.—Foucault's arc-light regulator of 1847. From E. Alglave and J. Boulard, *The Electric Light,* New York, 1884, p. 62.

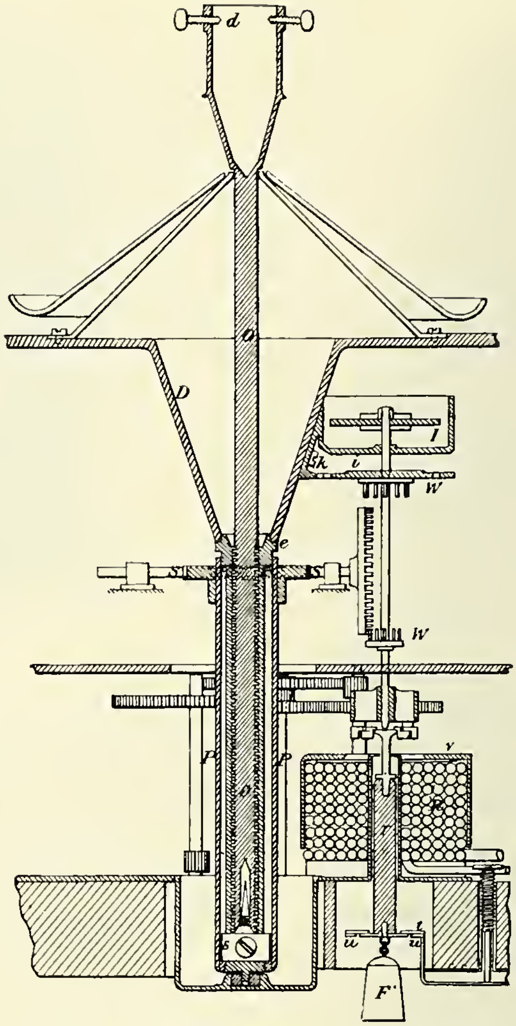

Figure 3.—Staite's 1847 regulator for changing the position of the lower carbon (placed in *d*) in his arc light. The upper carbon was fixed in position; the lower carbon's position was determined by a clockwork whose speed was controlled by a solenoid. From J. Dredge, *Electric Illumination,* London, n.d. (about 1882), vol. 1, p. 381.

ment-makers Deleuil. Archereau, and Duboscq during the 1840's.[2]

After a few private demonstrations in 1841, Louis J. Deleuil showed, in 1843, that he could light the Place de la Concorde by electricity (fig. 1).[3] The 200 Bunsen cells he placed below the statue of Lille produced a discharge between charcoal electrodes in an evacuated glass cylinder that was situated on the knees of the statue. The soft glow penetrated the slight fog on the evening of the demonstration, and the experiment was pronounced a success. Deleuil had been assisted in the trial by Henri A. Archereau who had used a similar method to light his dining room in 1843.[4] Archereau followed with other public demonstrations a short time later but without the feature of the evacuated globe. Nevertheless, such pioneer efforts were handicapped by the uneven burning of the carbons that made constant manual operation necessary for continuous performance.

[2] "Eclairage," *La Grande Encyclopédie,* Paris, n.d., vol. 15, pp. 341–346; Eugène Defrance, *Histoire de l'éclairage des rues de Paris,* Paris, 1904; Louis Figuier, *Les Applications de la science à l'industrie et aux arts en 1855,* Paris, 1856, pp. 326–336.

[3] *Les Mondes,* 1863, vol. 2, p. 452; *L'Illustration,* 1843, vol. 2, p. 132.

[4] J. Balteau, M. Barroux, and Michel Prévost, *Dictionnaire de biographie française,* Paris, 1939, vol. 3, p. 381.

Léon Foucault initiated progress toward a solution in 1844 with his photometric studies on the radiation from a carbon arc. He discovered that an electrode that was consumed more uniformly and more slowly than charcoal could be made from the hard carbonaceous deposit formed in coke retorts. He then set to work to devise an automatic regulator for the arc, but, in 1848, he was surprised to read that W. Edward Staite of London had applied for a patent on a regulator that appeared to be based on the same principle as his.[5] Upon invitation by Foucault, a committee from the Académie des Sciences examined his laboratory and verified that his work was independent of Staite's. However, Foucault's automatic regulator (fig. 2) for the arc was too delicate and too complicated for use even in the laboratory, and it found little application until it was modified by Duboscq.

Staite had begun his work by demonstrating an automatic arc light in a hotel at Sunderland, Durham, in 1847. This light (figs. 3, 4) had finally worked so well that it is said to have remained in use for several years. Public exhibitions in 1848 and 1849 led to what one might consider the first commercial success of the electric light. In May 1849 a ballet called "Electra," especially composed for the purpose, introduced the arc light to the public at Her Majesty's Theater in London (fig. 5). The ballet was an instant hit, and a command performance was given for Queen Victoria a few weeks later. A similar application appeared about the same time across the Channel, where Foucault's arc lamp was used to simulate the rising sun in Meyerbeer's latest opera, "Le Prophète." [6]

Staite constantly improved his apparatus. In 1849 the average time for continuous operation was 45 minutes; two years later his arc light could run without interruption for 5 hours. He even demonstrated it to the Queen and to her court at the palace. Then he obtained a request in 1852 that seemed to promise a profitable commercial venture. The port of Liverpool asked him to set up a permanent installation of his lamps on a high tower so as to permit work to

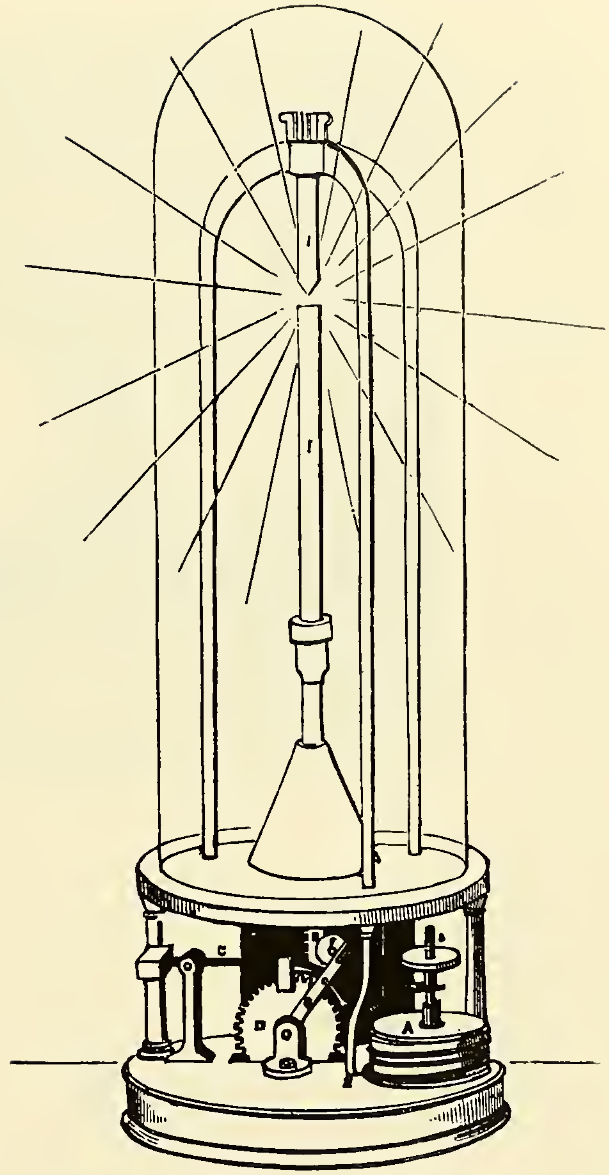

Figure 4.—Staite's arc light of 1848. From *Illustrated London News*, November 18, 1848, vol. 13, p. 317.

[5] *L'Illustration*, 1849, vol. 13, p. 6; Léon Foucault, "Appareil destiné à rendre constante la lumière émanant d'un charbon placé entre les deux pôles d'une pile," *Comptes rendus*, 1849, vol. 28, pp. 68–69; Théodose du Moncel, *Exposé des applications de l'électricité*, Paris, 1856–1862, ed. 2 (5 vols.), vol. 3, pp. 217–219.

[6] Emile Alglave and J. Boulard, *La Lumière électrique, son histoire, production et son emploi dans l'éclairage public ou privé*, Paris, 1882, translated by T. O'Connor Sloane as *The Electric Light*, New York, 1884, pp. 22–23; *Mechanics Magazine*, 1847, vol. 46, pp. 621–622; 1848, vol. 48, p. 453; vol. 49, p. 382; *Illustrated London News*, 1848, vol. 13, pp. 317, 343, 368, 378; 1849, vol. 14, p. 58; *London Times*, November 2, 1848; *Illustrated London News*, 1849, vol. 14, p. 293; Jules A. Lissajou, in *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1868, ser. 2, vol. 15, p. 59. Although the *Illustrated London News* asserts the device was copied in France, Lissajou claims it was used on April 16, 1849, the opening date for Meyerbeer's opera.

Figure 5.—Scene from the last act of the ballet "Electra, or the Last Pleaid." From *Illustrated London News*, May 5, 1849. vol. 14, p. 293.

be carried on at night. These preliminary results [7] were very encouraging, but Staite's death brought an end to the project.

A portion of Staite's success was due to his invention of a practical automatic regulator that eliminated the necessity of moving the carbons by hand as they were consumed (fig. 6).[8] The amount of current flowing through the arc controlled the spacing of the carbons by balancing a mechanical force with the attractive force of a solenoid. As the carbons burned, the arc became longer and the current became less due to the increased resistance. The decreased attractive force of the solenoid permitted the carbons to move closer together in Staite's 1847 regulator by controlling a clockwork and in his 1853 regulator by controlling the height of a float. This solenoid control came to be a basic feature in the design of all the later successful regulators. Other factors contributing to the success of Staite's lamp were the semi-enclosure of the arc in a chamber to reduce the consumption of the carbons (a feature that was not again used until the 1890's, but then with great success) and the use of the hard carbon from coke retorts rather than the much softer charcoal. Foucault's regulator was based on the same solenoid principle as that of Staite's, but it was set up horizontally so that, as the attractive force due to the solenoid became weaker due to the lengthened arc, a detent released a clockwork that moved the electrodes together.

In the meantime, other regulators had appeared (figs. 8, 9). In France, Archereau, in 1849, also invented a regulator that balanced the weight of the carbon electrode against the attractive force of a solenoid (fig. 10), but the system was too insensitive

[7] *Mechanics Magazine*, 1849, vol. 50, pp. 538–539; 1850, vol. 52, p. 35; 1851, vol. 54, pp. 411–412; vol. 55, pp. 316–317; 1852, vol. 57, p. 217.

[8] British patents 11449 (November 12, 1846), 11783 (July 3, 1847), 12212 (July 12, 1848), 12772 (September 20, 1849), 634 (March 14, 1853); *Mechanics Magazine*, 1848, vol. 48, pp. 49–56; 1849, vol. 50, pp. 49–58, 73–80; 1850, vol. 52, pp. 246–248; *Illustrated London News*, January 1849, vol. 14, p. 58.

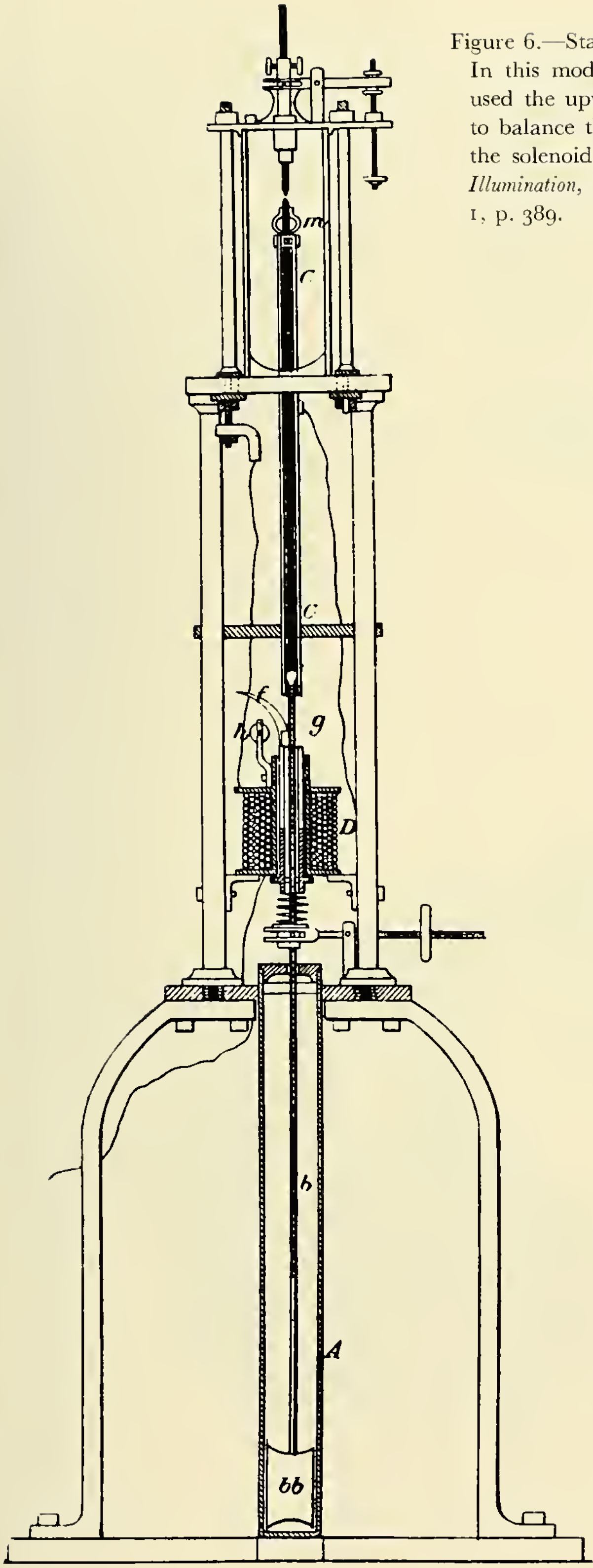

Figure 6.—Staite's arc-light regulator of 1853. In this modification of his invention Staite used the upward buoyancy of the float (*bb*) to balance the downward pull of the coil of the solenoid (*D*). From J. Dredge, *Electric Illumination*, London, n.d. (about 1882), vol. 1, p. 389.

and irregular in its action.[9] However, this regulator seemed so promising that after Archereau demonstrated it in a St. Petersburg square Czar Nicholas requested the Russian Academy of Sciences to investigate streetlighting by this method.[10] Then, in 1855, Archereau sought to illuminate the port of Marseilles with his arc lamp.[11]

In 1850 Duboscq simplified Foucault's regulator to the extent that it became sufficiently reliable for regular use in the theater as well as for laboratory and lecture demonstrations (figs. 11, 12). The use of the brilliant arc light became so necessary for spectacular effects that finally, in 1855, an entire room at the Paris Opera House was set aside for Duboscq's electrical equipment. The prizes at the Exposition Universelle of Paris in 1855 were handed out in the brilliance of this regulator, with one of the awards going to Duboscq for his invention; other prizes and honors followed successive improvements in the regulator.[12] However, the regulator was still too delicate, and there was a disadvantage in that the clockwork required winding.

Except for Staite's lamp, these early regulators were satisfactory only for a relatively short period of

[9] British patent 7924 (February 12, 1849); Du Moncel, *op. cit.* (footnote 5).

[10] *Illustrated London News*, December 1, 1849, vol. 15, p. 362.

[11] *Les Mondes*, 1863, vol. 2, p. 452.

[12] Jules Duboscq, "Note sur un régulateur électrique," *Comptes rendus*, 1850, vol. 31, pp. 807–809; Edmond Becquerel, "Rapport . . . sur l'appareil photo-électrique de M. Jules Duboscq, opticien," *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1855, ser. 2, vol. 2, pp. 455–461; Hippolyte Fontaine, *Eclairage à l'électricité*, Paris, 1877, p. 11; *La Lumière électrique*, 1880, vol. 2, pp. 284–288; *Cosmos*, 1855, vol. 7, pp. 492–494; 1864, vol. 24, pp. 121–126; Du Moncel, *op. cit.* (footnote 5), vol. 3, pp. 221–231, 280; *L'Année scientifique*, 1856, vol. 1, pp. 485–486; *Mechanics Magazine*, 1857, vol. 67, p. 250; 1858, vol. 68, pp. 252–253; Jules A. Lissajou, in *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1859, ser. 2, vol. 6, p. 254.

Figure 7.—How a French cartoonist imagined the lodger of the future would be given his electric "candle" by the concierge. From *L'Illustration*, September 30, 1848, vol. 12, p. 69.

time, and so other means of regulating the carbons were sought. Joseph Lacassagne and Rodolphe Thiers devised a differential arc light regulator in which the current resulting from the difference of two controlling circuits fed the moving carbon at the proper speed (figs. 14, 15). By using a battery of 60 Bunsen cells, Lacassagne and Thiers successfully illuminated a square in their home city of Lyons in 1855, and the following year they lit up the Arc de l'Etoile and the Avenue des Champs Elysées for four hours in a vain attempt to interest Napoleon III in their invention. After successful trials at Lyons again, where they used two lamps to light the Rue Impériale during the evenings for the entire month of March 1857, Lacassagne died; in the same year the Société d'Encouragement pour l'Industrie Nationale awarded a bronze medal for the Lacassagne and Thiers regulator. Thiers sought to exploit the

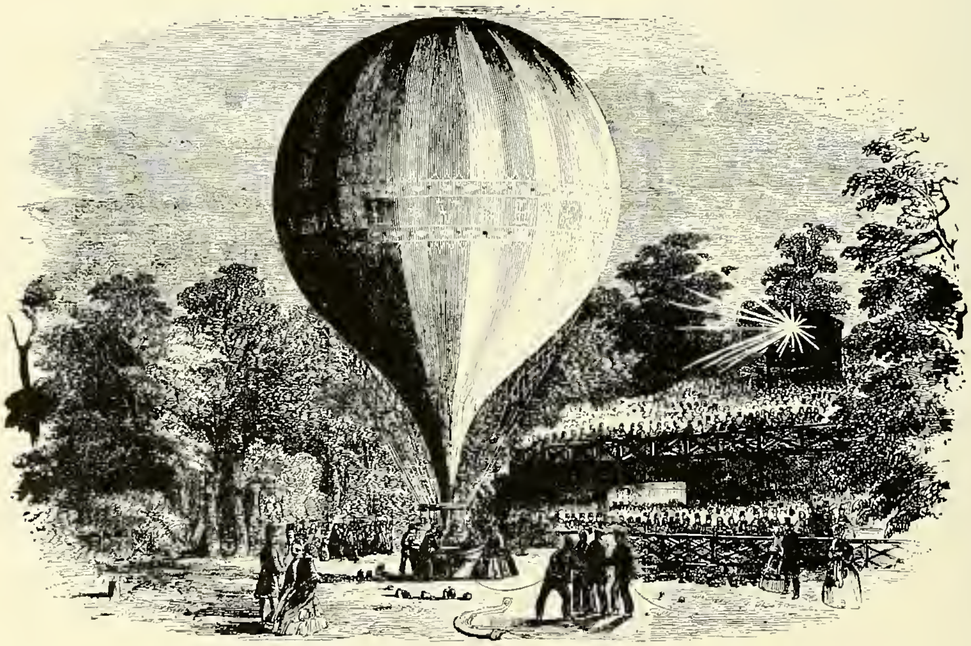

Figure 8.—Demonstration of the new electric light at a balloon ascension at The Vauxhall in London. From *Illustrated London News*, August 25, 1849, vol. 15, p. 144.

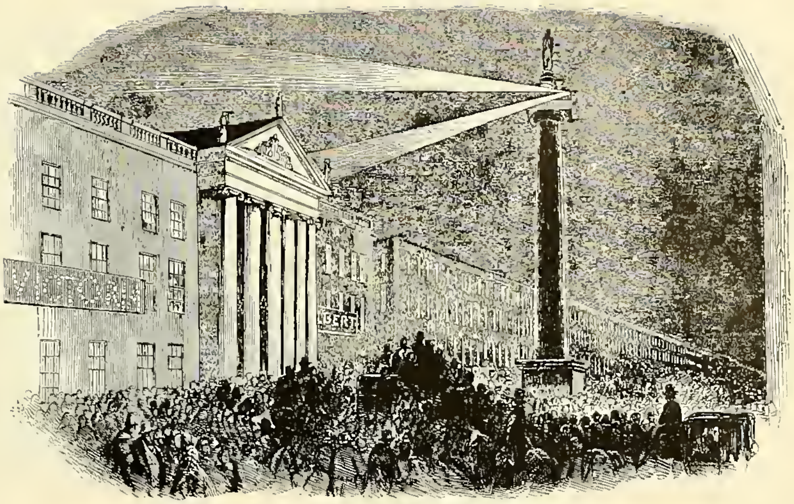

Figure 9.—Demonstration of the new electric light during a visit of Queen Victoria and Prince Albert to Dublin, Ireland. From *Illustrated London News*, August 11, 1849, vol. 15, p. 96.

invention after the death of his partner but without any signs of permanent success.[13]

Then, in 1857, Victor Serrin invented a regulator based on some of the best features of that of Duboscq, and it dominated the field for two decades in France and elsewhere (fig. 16).[14] Further refinements made in 1859 produced *le modèle suisse* (fig. 17) that proved its superiority over all others.[15] The heart of its reliability rested in the use of two driving systems balanced against one another through a linkage in the form of a parallelogram with one of the vertical sides fixed (fig. 18). As the upper carbon was consumed and lost weight a detent was released, permitting a clockwork to raise the mobile vertical side of the parallelogram and, in turn, to raise the other carbon. The shortened arc allowed a greater current to flow through a solenoid that tended to pull down the mobile side of the parallelogram by means of an armature attached to the linkage. In this manner, a new balance was constantly found as the carbons gradually disappeared. As we shall see below, Serrin's final regulator (fig. 19) was the one used in the most successful demonstrations of the electric light until the end of the 1870's. A regulator somewhat similar to that of Serrin was produced by Siemens, and it came into wide use in Germany and England.

Complaints often were made that the arc light was too glaring, although it was pointed out to such critics that so, also, was the sun. Nevertheless, the intensity of the arc light proved to be a stumbling block to the use of electricity for public lighting. Various efforts were made to reduce the brightness. The intensity of the arc light was reduced by placing it on very high supports, and various kinds of diffusers, such as frosted glass, were tried. Another possibility considered was that perhaps the electric light could be subdivided by placing several arc lights in the same circuit. If this could be achieved, the glow could be spread over a number of sources. Both Quirini and Deleuil asserted that they had placed

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[13] British patent 2456 (October 20, 1856); Edmond Becquerel, "Rapport sur un régulateur électrique et sur une lampe photo-électrique presentés par MM. Lacassagne et Thiers de Lyons," *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*,1856, ser. 2, vol. 3, p. 672, and 1857, ser. 2, vol. 4, pp. 524–547; Du Moncel, *op. cit.* (footnote 5), vol. 3, pp. 234–239; vol. 4, pp. 504–506; *Cosmos*, 1856, vol. 9, pp. 365–368; 1857, vol. 10, pp. 342–343, 538–539; 1859, vol. 15, pp. 200–202; 1861, vol. 19, p. 113; *L'Illustration*, 1856, vol. 28, p. 299; *Mechanics Magazine*, 1857, vol. 66, pp. 529–530; *L'Année scientifique*, 1858, vol. 2, p. 488; *Les Mondes*, 1863, vol. 1, pp. 311–312.

[14] *Les Mondes*, 1867, vol. 14, pp. 543–555; Du Moncel, *op. cit.* (footnote 5), vol. 4, pp. 492–500.

[15] French patent 38506 (October 23, 1858; addition, October 22, 1859); British patent 653 (March 15, 1859); Victor L. M. Serrin, "Régulateur automatique de lumière électrique," *Comptes rendus*, 1860, vol. 50, pp. 903–905; *Cosmos*, 1860, vol. 16, pp. 514–517; F. P. Le Roux, "Rapport sur . . . un régulateur automatique de lumière électrique présenté par M. Serrin," *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1861, ser. 2, vol. 8, pp. 647–654 (see also 1860, ser. 2, vol. 7, p. 317, and 1866, ser. 2, vol. 13); *Les Mondes*, 1866, vol. 11, pp. 666–668,

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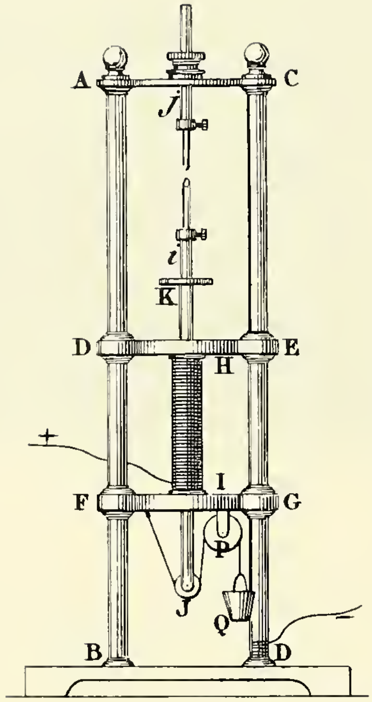


Figure 10.—Archereau's arc-light regulator. The downward weight of the lower carbon was balanced by the upward pull of the solenoid core. From T. du Moncel, *Exposé des applications de l'électricité*, Paris, ed. 2, 1856–1862, vol. 3, pl. 4, fig. 3.

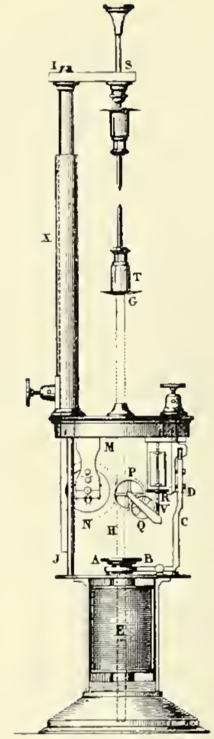


Figure 11.—Duboscq's version of the Foucault arc-light regulator. The rate of ascension of the lower carbon was controlled by a clockwork whose escapement was controlled by the solenoid (E). From T. du Moncel, *Exposé des applications de l'électricité*, Paris, ed. 2, 1856–1862, vol. 3, pl. 4, fig. 4.

several arc lights in the same circuit, the former in 1849 and the latter in 1855. However, such a circuit could be maintained only for a short time.[16] After considerable study, L. F. Wartmann, of Switzerland, asserted that the electric light could be subdivided but that the method depended on the system used in the distribution of the illumination.[17]

However, until the end of the 1870's, all regulators were inherently unstable when placed in the same circuit, except possibly one. When placed in series, if one went out, they all went out; and when placed in parallel, one tended to quench the others. The only kind of regulator that did not have this innate defect was that of Lacassagne and Thiers, but it is difficult to determine to what extent this advantage was realized in practice by the inventors.[18] At any rate, the consensus was that it was not possible to subdivide the electric light.

In the decade between 1855 and 1865 a number of attempts were made to use the arc light for military operations and for public celebrations. It has been said that the arc light was tried during the naval attack on Kinburn in 1855 during the Crimean War, and in 1859 during the Italian war of independence. Joseph Henry devised an arc light in 1863 that was intended to be used for the siege of Charlestown during the Civil War, and in the same year Boston celebrated Union victories by arc-light illumination. On the occasion of the visit of Queen Isabella II of Spain to Paris in 1864, Napoleon used 11 Serrin regulators to illuminate the fountains of

[16] *Cosmos*, 1855, vol. 7, pp. 703–704; 1856, vol. 8, pp. 30–32.

[17] L. F. Wartmann, "Sur l'Eclairage électrique," *Bibliothèque Universelle de Genève, Archives des sciences physiques et naturelles*, 1857, vol. 36, pp. 323–334.

[18] Du Moncel, *op. cit.* (footnote 5), vol. 3, pp. 250–251.

Figure 12.—Use of the Duboscq arc light to produce a rainbow for a scene in the opera "Moses" at the Paris Opera House in 1860. From *La Lumière électrique*, July 15, 1880, vol. 2, p. 287.

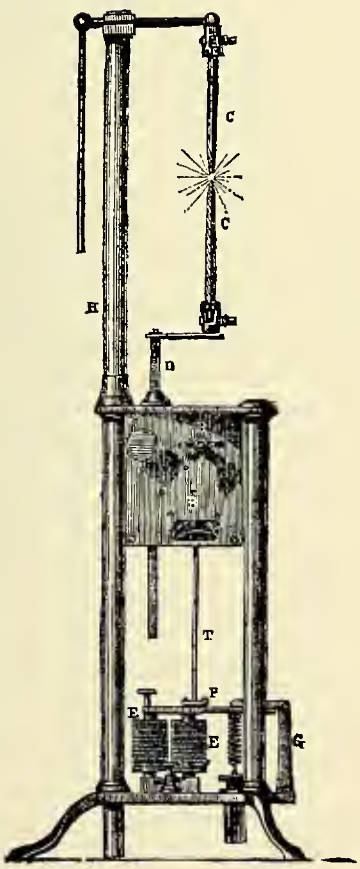


Figure 13.—A later version (1864) of the Duboscq arc-light regulator. From *Cosmos*, January 28, 1864, vol. 24, p. 122.

Versailles.[19] Nevertheless, neither the military nor peacetime applications of the arc light took root in contemporary technology. The problems of how to make carbons for the arcs and of how to maintain the carbons at the proper distance and in the same place were more or less solved by 1860, but such endeavors were premature and could have no lasting results until an adequate source of electrical power could be found.

Chemical cells had been used as a source of power for the arc lamp but they were admittedly quite expensive. A number of studies had been made showing just how much greater was the cost of producing light by Bunsen cells than by gas or oil, and E. Becquerel concluded that, in Paris, the cost of such light was at least six times that of gas.[20] Another factor that had to be considered was that the acids used constantly gave off noxious fumes and were dangerous for

[19] "Eclairage," *La Grande Encyclopédie*, Paris, n.d., vol. 15, pp. 341–346; Hippolyte Fontaine, *Eclairage à l'électricité*, Paris, 1879, ed. 2, p. 242 (this may refer to the use of electrically detonated mines in the defense of Venice rather than to the electric light; see *Journal of the Telegraph*, New York, 1868, vol. 1, no. 25, p. 3); Joseph Henry to Alexander Bache, August 21, 1863, in archives of the Smithsonian Institution; *Boston Daily Advertiser*, August 8, 1863; *American Journal of Science*, 1863, ser. 2, vol. 36, pp. 307–308.

[20] Becquerel, *op. cit.* (footnote 13); *Cosmos*, 1857, vol 9, pp. 417–420.

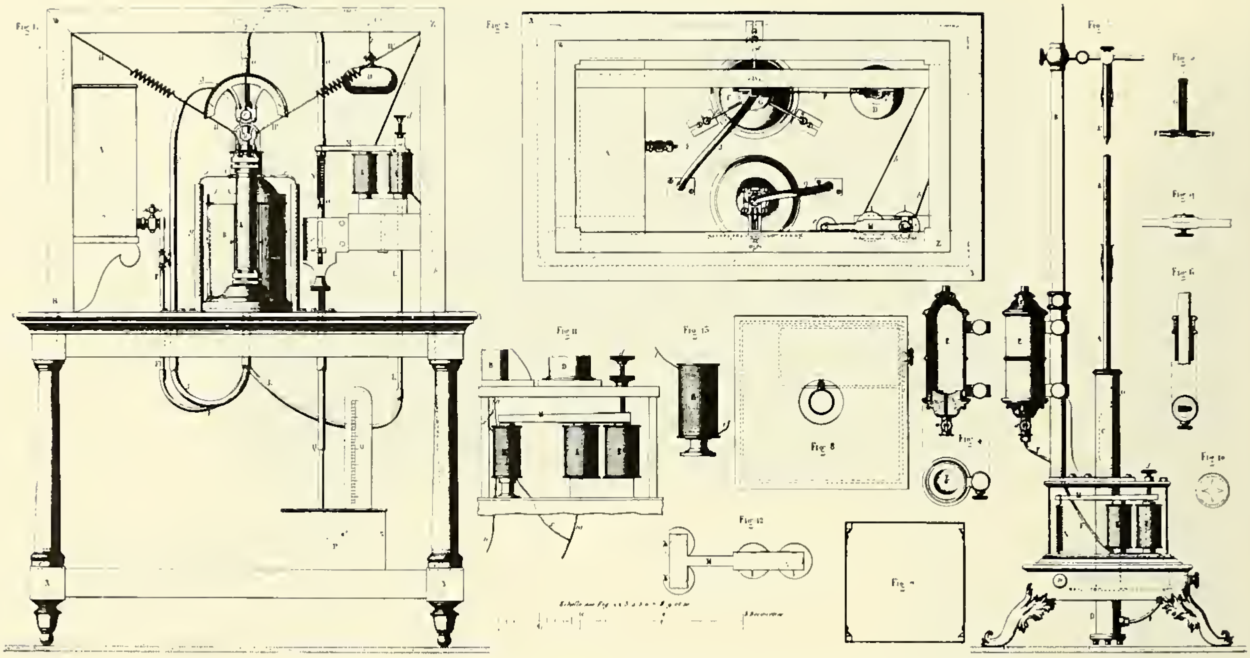


Figure 14.—Current regulator and arc-light regulator of Lacassagne and Thiers. From *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1857, vol. 4, pl. 113.

unskilled workmen to handle. Moreover, even with the best cells of the time, the power was such that the light was appreciably reduced after several hours use. If the light were to be maintained constant, a new battery had to be switched into the circuit. In addition, the cells were too bulky (at least 20 Bunsen cells had to be used for each arc lamp) and too fragile for any extensive application to the industrial arts.

There was a laboratory device on hand, however, that did not depend on the consumption of metals to produce electrical power but, instead, transmuted mechanical power into electrical. The reciprocal relation between mechanical motion and electrical current was discovered in the early 1830's, but almost half a century passed before it was possible to apply this knowledge to the commercial generation of electrical power. Such an application did not become possible until the device known as the dynamo was invented, but simpler generators were well known in the laboratory before that date. Once it had been shown that these generators could be used to supply power for illumination by electricity, a number of inventors sought to bring them from the laboratory into the field of commerce. This laboratory instrument was based on Faraday's discovery of electromagnetic induction, and we must briefly return to the 1830's to discuss the development of the generator.

Like Oersted, although for somewhat different reasons, Michael Faraday felt that all the forces of nature must be somehow related. In particular, if a certain relation exists between two different forces, the converse of that relation must also exist. Such considerations led Faraday to seek an effect opposite to that of Oersted—that of obtaining an electric current from magnetism. He finally discovered it in the relative motion of a magnet with respect to a closed circuit (fig. 20). Investigation of the same relation was pursued by Joseph Henry about the same time, but his delay in publishing the results has tended to obscure his contributions.[21]

Mechanical devices that continuously transform energy from a mechanical to an electrical form followed within a few months of Faraday's discovery of induction. One of the first such devices was

[21] Michael Faraday, "Experimental Researches in Electricity," *Philosophical Transactions*, 1832, vol 122, pp 125–162; A. Fresnel, "Note sur des essais ayant pour but de décomposer l'eau avec un aimant," *Annales de chimie et de physique*, 1820, ser. 2, vol. 15, pp. 219–222; Joseph Henry, "On the Production of Currents and Sparks of Electricity from Magnetism," *American Journal of Science*, 1832, vol. 22, pp. 403–408.

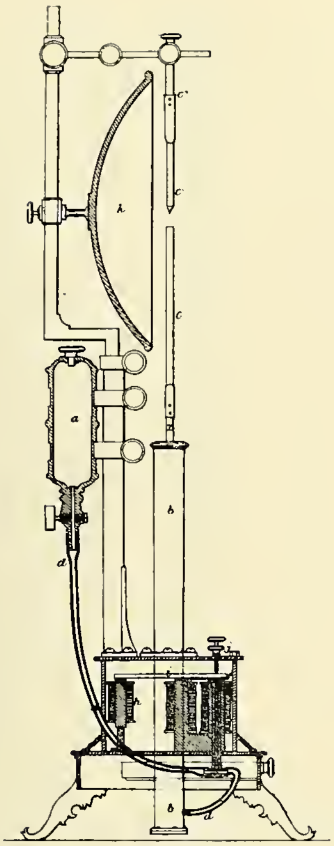


Figure 15.—Another form of the differential arc-light regulator of Lacassagne and Thiers. Two circuits—one permitting and one stopping the flow of mercury from the reservoir (*a*)—controlled the position of the float, to which the lower carbon was fixed. A similar differential principle formed the basis for all the later successful regulators. From J. Dredge, *Electric Illumination*, London, n.d. (about 1882), vol. 1, p. 392.

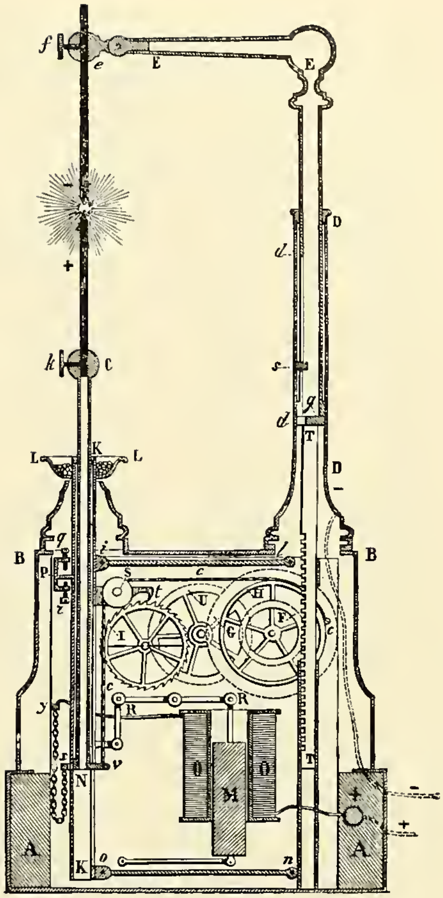


Figure 16.—One of the earliest (1857) versions of Serrin's arc-light regulator. From T. du Moncel, *Exposé des applications de l'électricité*, Paris, ed. 2, 1856–1862, vol. 4, p. 493.

invented by Faraday himself in November 1831. He called this new device a magnetoelectric generator, in contrast to the electrostatic generator; later, the term was shortened to "magneto." This first magnetoelectric generator was, interestingly enough, the converse of Barlow's "wheel," a simple electric motor. Faraday's generator could not produce sparks or electrolyze water, but it did deflect the needle of a galvanometer.

A somewhat more efficient device was produced by Hippolyte Pixii, who had been instrument-maker to D. F. J. Arago and A. M. Ampère for a number of years. Pixii's magneto generator (fig. 21), which was first demonstrated in a lecture by Ampère at the Sorbonne in September 1832, consisted of a 2-kg. horseshoe magnet mounted on a vertical axis that could be rotated before the poles of an electromagnet that acted as armature to the magnet. The electromagnet was about 8 cm. high and had 50 meters of copper wire on it. The alternate passage of first a north and then a south pole before the poles of the electromagnet produced an alternating current that went first in one direction along the wire and then the other, in contrast to the current from chemical cells that always went in the same direction. Although the resulting gases were mixed, Pixii's magneto

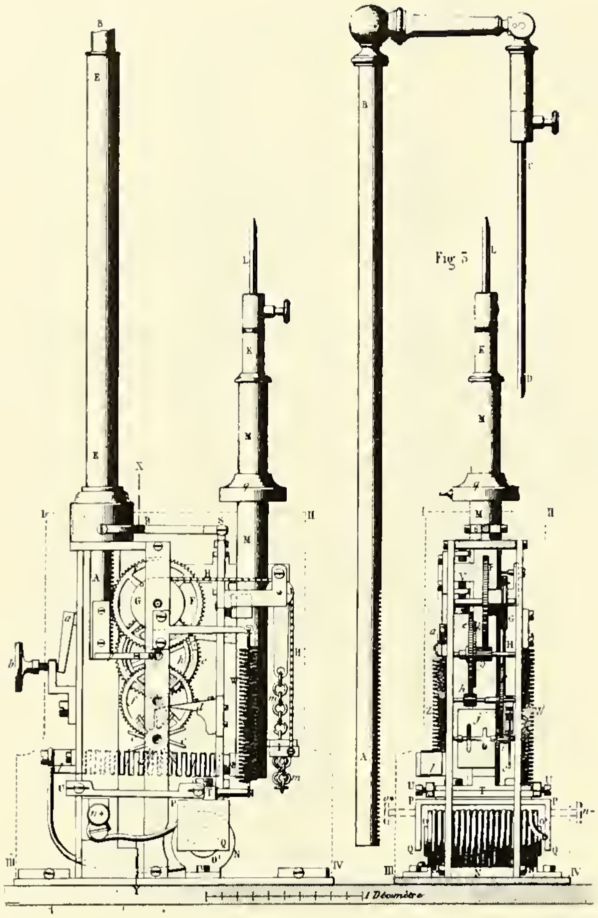


Figure 17.—Serrin's *modele suisse* arc-light regulator. From *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1861, vol. 8, pl. 234.

could electrolyze water and was a great improvement over Faraday's.[22]

In the month following his Sorbonne demonstration Ampère reported how Pixii had built a much larger generator than before and had modified Ampère's commutator switch so that it could be used with the generator (fig. 22).[23] A cam on the axis of the armature actuated the commutator that reversed the directions of the alternations at the appropriate time so as to obtain a more or less unidirectional current. The magneto now provided a current similar to that from the chemical cell, and the gases resulting from the electrolysis of water were in the correct proportions.

Since it was also possible to rotate the coils making up the armature and to keep the magnets stationary, such modifications soon appeared. One of the first of these was described in a report given by the Rev. William Ritchie in March 1833 on a magnetoelectric generator (fig. 23) that he had worked out during the previous summer.[24] Ritchie's armature, in the form of a disk that rotated about an axis perpendicular to its plane, consisted of four coils, 90° apart, that were mounted between two wheels with the axes of the coils parallel to the axis of the supporting wheels. When the armature was rotated, the coils passed in succession between the poles of a permanent magnet and produced an alternating current. In order to obtain a unidirectional or direct current from the rotating armature, Ritchie devised a commutator switch that was mounted directly on the axis of the armature.

Other, more practical forms of the Pixii magneto generator were devised a few years later by instrument-makers Joseph Saxton of Washington and Edward Clarke of London.[25] Their magnetos became quite popular for laboratory demonstrations and for medical experiments. Saxton modified Pixii's generator by

[22] Jean N. P. Hachette, "Nouvelle Construction d'une machine électromagnétique," *Annales de chimie et de physique*, 1832, vol. 50, pp. 322–324, and "De l'Action chimique produite par l'induction electrique; décomposition de l'eau," *Annales de chimie et de physique*, 1832, vol. 51, pp. 72–74; Charles Jackson, "Notice of the Revolving Electric Magnet of Mr. Pixii of Paris," *American Journal of Science*, 1833, vol. 24, pp. 146–147; *Gehler's physikalisches Woertcrbuch*, Leipzig, 1836, new ed., Band 6/2, pp. 1177–1180.

[23] André M. Ampère, "Note de M. Ampère sur une expérience de M. Hippolyte Pixii, relative au courant produit par la rotation d'un aimant, à l'aide d'un appareil imaginé par M. Hippolyte Pixii," *Annales de chimie et de physique*, 1832, vol. 51, pp. 76–79.

[24] William Ritchie, "Experimental Researches in Electro-Magnetism and Magneto-Electricity," *Philosophical Transactions*, 1833, vol. 123, pp. 313–321.

[25] Joseph Saxton, "Description of a Revolving Keeper Magnet, for Producing Electrical Currents," *Journal of the Franklin Institute*, 1834, vol. 13, pp. 155–156; Edward M. Clarke to the editors, *Philosophical Magazine*, 1836, vol. 9, pp. 262–266; "A Description of a Magnetic Electrical Machine," *Annals of Electricity*, 1837, vol. 1, pp. 145–155; "Reply of Mr. E. M. Clarke to Mr. J. Saxton," *Philosophical Magazine*, 1837, new ser., vol. 10, pp. 455–459; "Account of a Series of Experiments Made with a Large Magneto-Electrical Machine," *Transactions and Proceedings of the London Electrical Society*, 1837–1840, vol. 1, pp. 73–76.

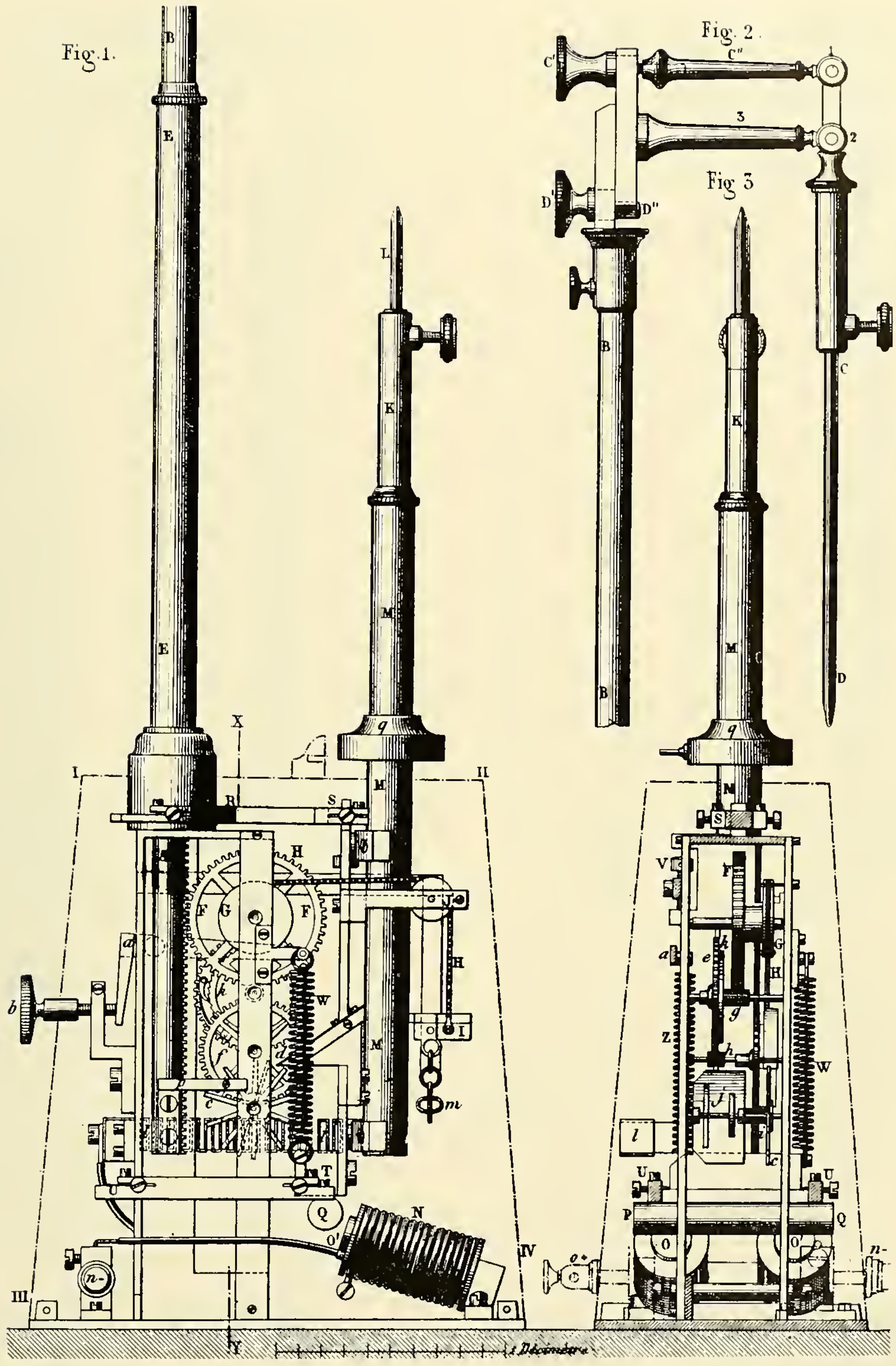


Figure 18.—Improved version (1867) of Serrin's arc-light regulator. From *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1867, vol. 14, pl. 371.

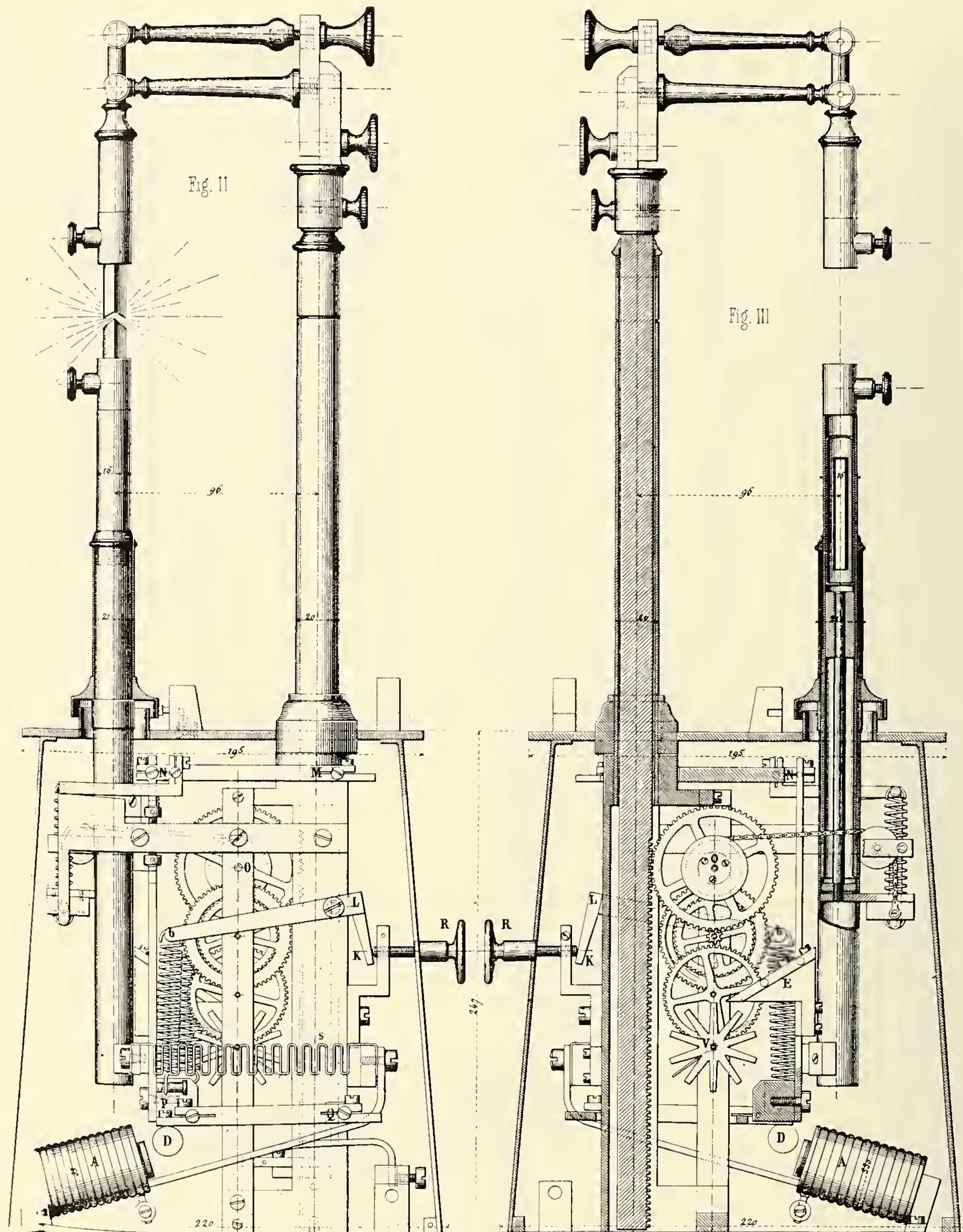


Figure 19.—Final version (1876) of Serrin's arc-light regulator. From *Revue industrielle*, May 3, 1876, p. 181, pl. 12.

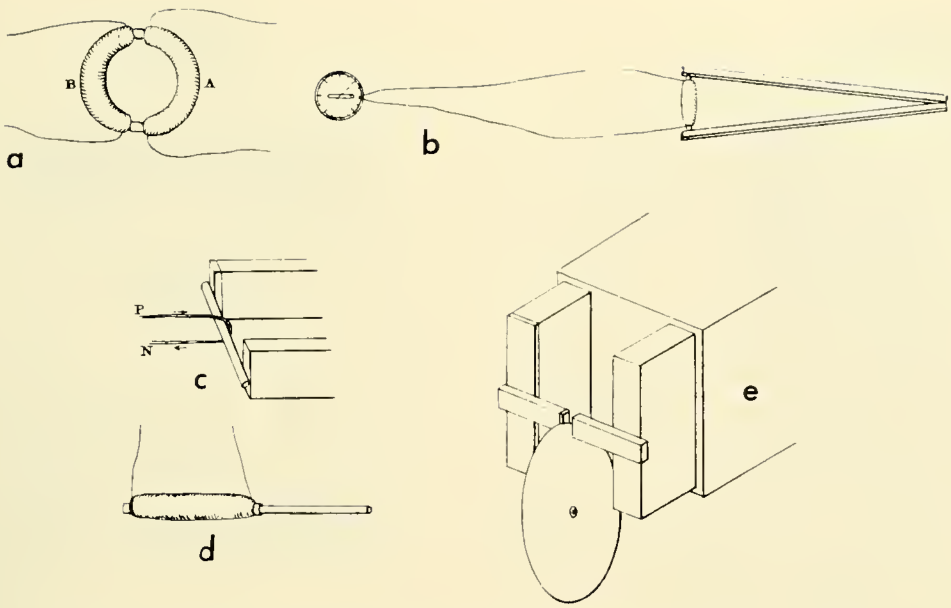


Figure 20.—Some of the various means used by Faraday to induce an electric current by magnetism: (*a*) coil to induce a momentary current in another coil by making or breaking the galvanic circuit in the first coil, (*b*, *c*) inducing a momentary current by making or breaking a magnetic circuit, (*d*) inducing a momentary current by moving a magnet through a coil of wire, and (*e*) inducing a continuous current by rotating a conducting disk in a magnetic field. The last was the converse of the Barlow wheel experiment. From *Philosophical Transactions*, 1832, vol. 122, pl. 3.

using three instead of two coils, by replacing the single magnet by a compound one, and by placing the axis of the instrument horizontally instead of vertically (fig. 24). Clarke used only a pair of coils, but sought to increase the current by rotating the coils beside the poles instead of in front of the poles as in the Pixii and Saxton machines. Clarke made two sets of coils for his magneto, one of fine wire for high voltage and the other of coarse wire for large currents (figs. 25, 26).

Charles Page, of Washington, increased the output of Clarke's magneto by increasing the intensity of the magnetic field. He placed another compound magnet parallel to that of the Clarke machine and then rotated the coils between the two compound magnets (figs. 27, 28). Such devices were made commercially

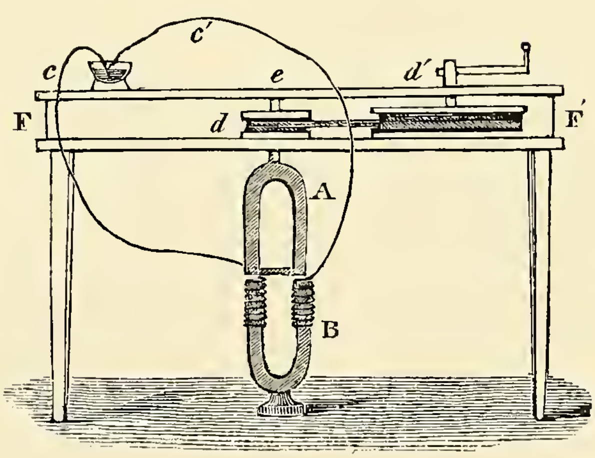


Figure 21.—Pixii magneto generator, without commutator. From *American Journal of Science*, April 1833, vol. 24, p. 146.

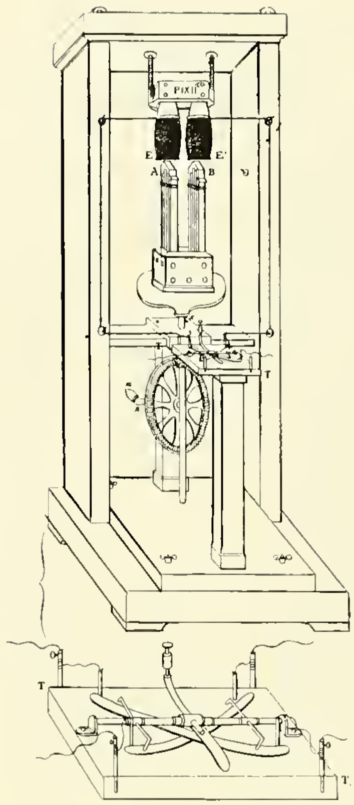


Figure 22.—Pixii magneto generator with Ampère's commutator, which is shown enlarged at the bottom of the figure. From H. W. Dove and L. Moser, *Repertorium der Physik*, Berlin, 1837, vol. 1, pl. 2.

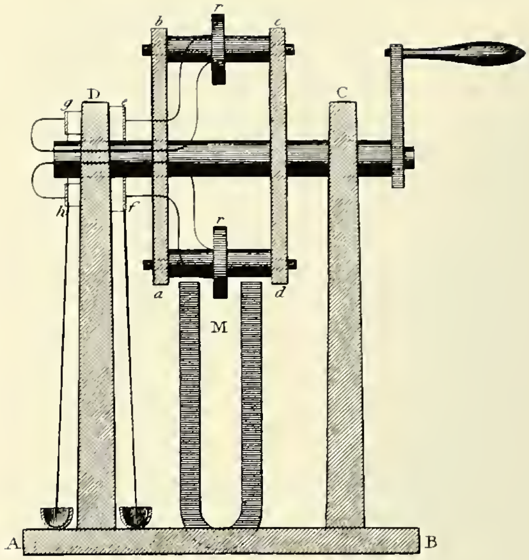


Figure 23.—Ritchie's magneto generator. The armature was shaped in the form of a disk, in which the coils (*r*) passed in succession between the poles of the magnet (M). The commutator is at *efgh*. From William Ritchie, "Experimental Researches in Electro-Magnetism and Magneto-Electricity," *Philosophical Transactions*, 1833, vol. 123, pl. 7 (opposite p. 316).

by Daniel Davis, of Boston, beginning in the spring of 1838.[26]

Most of the preceding instruments of the 1830's were essentially laboratory instruments constructed for experimental purposes. One of the earliest commercial applications of magneto generators was made by John S. Woolrich of Birmingham, England, in the following decade. In his patent application of 1841, Woolrich described how Saxton generators could be modified for electroplating, and his method seemed feasible enough to be tried by the Elkington firm in Birmingham, the same English firm that had already pioneered in electroplating.[27]

Three years later Woolrich designed a more ambitious generator (fig. 29) that was basically similar to Ritchie's. Coils and magnets were added to the Ritchie apparatus so that now a disk armature of eight uniformly spaced coils rotated between the poles of four magnets spaced 90° apart. The whole was built in a wooden framework that was 5 feet 4 inches high, 6 feet wide, and 2 feet deep. Faraday is said to have inspected Woolrich's generator and to have been delighted with this application of electromagnetic induction. The device was sold to the Prime Plating Company, of Birmingham, who used it for many years.[28]

[26] Charles Page, "New Magnetic Electrical Machine of Great Power, with Two Parallel Horse-Shoe Magnets, and Two Straight Rotating Armatures, Affording Each, in an Entire Revolution, a Constant Current in the Same Direction," *American Journal of Science*, 1838, vol. 34, pp. 163–169; Daniel Davis, *Manual of Magnetism*, Boston, 1847, ed. 2, pp. 277–282.

[27] British patent 9431 (August 1, 1841); *Mechanics Magazine* 1843, vol. 38, pp. 145–149.

[28] *Industrial Britain*, November 1938, no. 74, p. 1; J. Hamel, "Colossale magneto-elektrische Maschine zum Versilbern und Vergolden," *Journal fuer practische Chemie*, 1847, vol. 41, pp. 244–255.

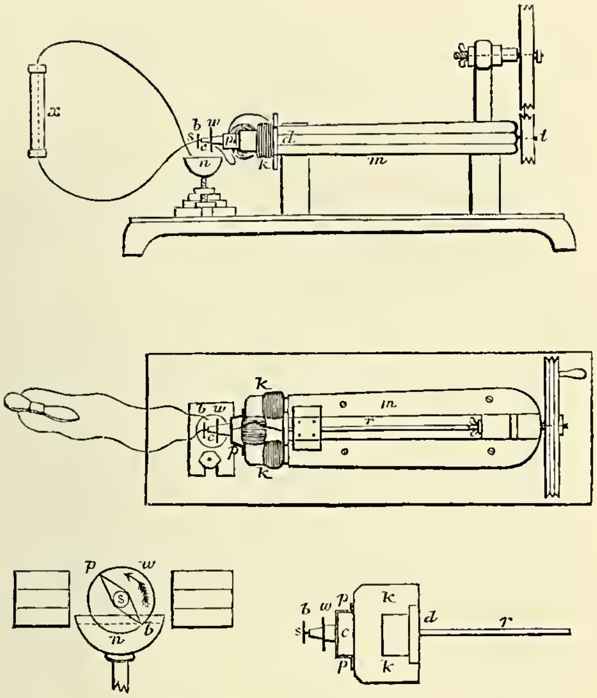


Figure 24.—Saxton's magneto generator. From *Journal of the Franklin Institute*, 1834, vol. 13, p. 155.

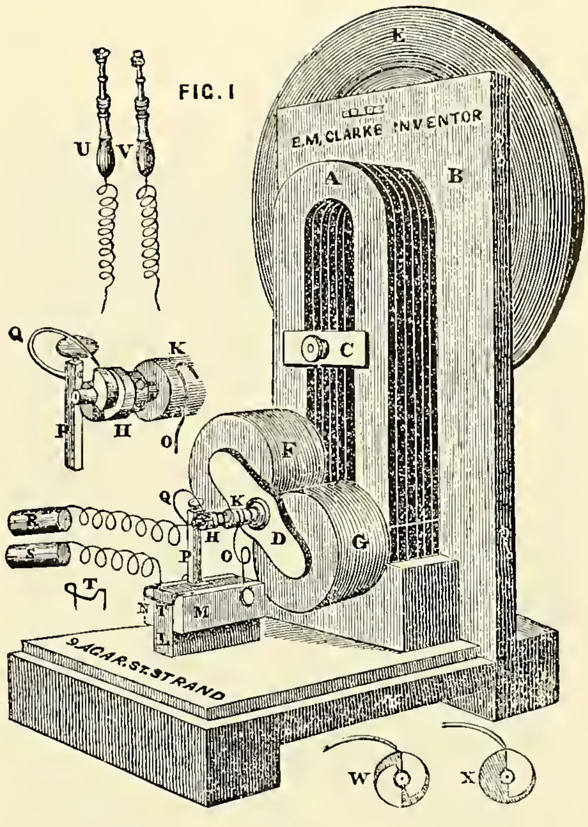


Figure 25.—Clarke's magneto generator. From *Annals of Electricity*, January 1837, vol. 1, p. 146.

Although Elkington felt that the magnetoelectric machine did not replace the voltaic cell, Woolrich, during the following decade, constructed similar machines (figs. 30, 31) for Elkington[29] and a few other electroplating companies in Birmingham.[30] In 1851, William Millward, of Birmingham, patented a machine [31] (fig. 32) that was very similar to Woolrich's.

A few years later a more important application of the magnetoelectric machine was demonstrated—one that had many implications for the future. Frederick H. Holmes showed, in 1853, that a magneto might be used to run an arc light, much to the surprise of the well known authority on electricity, E. Becquerel.[32] The latter subsequently declared that "none but a fool or an Englishman would have believed it possible."

After several years of experimentation, Holmes patented in 1856 a multiple disk armature machine consisting of many Woolrich generators mounted in a single frame (fig. 33).[33] Instead of one disk armature that rotated between the poles of a single bank of permanent magnets, Holmes spun six disk armatures on a common axis between seven parallel banks of permanent magnets. Every other disk was displaced through a small angle so as to reduce the fluctuations of the total induced current. The

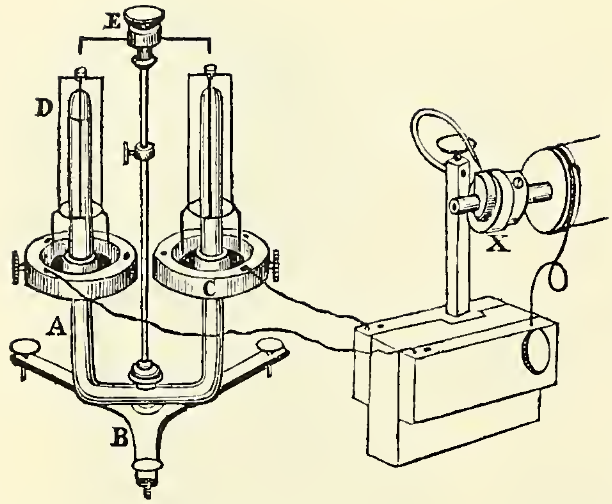
[29] *Mechanics Magazine*, 1849, vol. 51, pp. 271–272; *Illustrated London News*, October 2, 1852, vol. 21, p. 295.

[30] Samuel Timmins, *Birmingham and the Midland Hardware District*, London, 1866, pp. 488–494.

[31] British patent 13536 (February 28, 1851).

[32] D. K. Clark, *The Exhibited Machinery of 1862*, London, 1864, pp. 286, 431; J. H. Gladstone, "Lighthouse Illumination by Magneto-Electricity," *Quarterly Journal of Science*, 1864, vol. 1, pp. 70–75; *Les Mondes*, 1864, vol. 4, pp. 57–61.

[33] British patent 573 (March 7 and September 6, 1856). This is not the first patent of a Woolrich disk armature machine. As noted earlier in this paper, William Millward took out a patent on a single disk armature machine in 1851. Later this paper will discuss a patent on a multiple disk armature machine taken out in 1852 by E. C. Shepard for Florise Nollet.



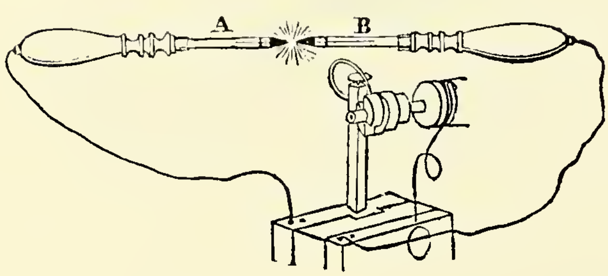


Figure 26.—Clarke's use of his magneto generator to produce rotary motion (top) and an arc between charcoal points (bottom). From *Annals of Electricity*, January 1837, vol. 1, p. 154.

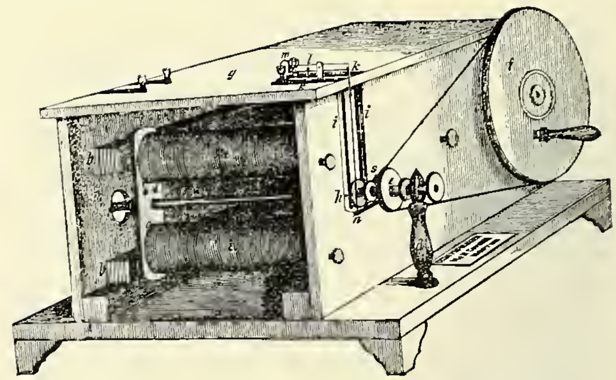


Figure 27.—Davis' first version of Page's magneto generator. From Charles Page, "New Magnetic Electrical Machine . . . ," *American Journal of Science*, July 1838, vol. 34, p. 164.

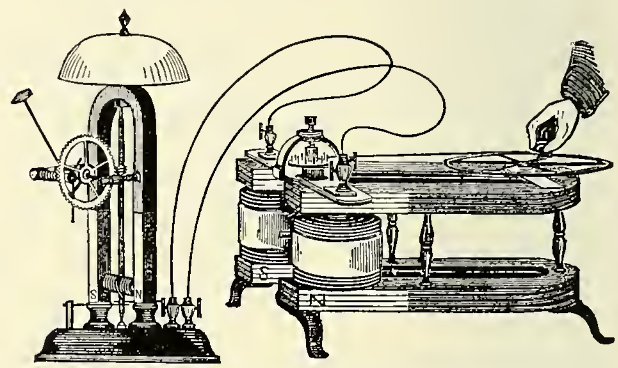


Figure 28.—Davis' improved version of Page's magneto generator, shown here ringing a bell. From D. Davis, *Manual of Magnetism*, Boston, ed. 13, 1869, p. 281.

current collectors were rollers that touched the commutator bars; they were placed about 60° apart, with their positions controlled by the speed of rotation.

In February 1857, Holmes suggested a possible application for the new electric light system. While considerable progress had been made during the 19th century in increasing the safety of marine commerce, the measures taken were still insufficient. Several decades earlier the Fresnel lens system had been added to the improved Carcel lamp, and new fuels had been discovered that gave a brighter light; although the effectiveness of the lighthouses was thereby increased, they were still inadequate. In 1867 the British Board of Trade reported that in one year 1,333 lives and 2,513 vessels were lost in the inland and coastal waters of Great Britain.[34]

Holmes submitted his suggestion to Trinity House, the agency responsible for lighthouses along the coast of England, and proposed to the Elder Brethren of the organization that the combination of arc-light and magnetoelectric machines be used for lighthouses. Although Faraday, who was the scientific advisor to Trinity House at the time, had not been previously convinced of the practicality of the electric light, Holmes so persuaded him that, in May 1857, John

[34] A. G. Findlay, "On the Progress of the English Lighthouse System," *Journal of the Society of Arts*, 1858, vol. 6, pp. 238–249; *Cosmos*, 1868, ser. 3, vol. 3, pp. 691–693.

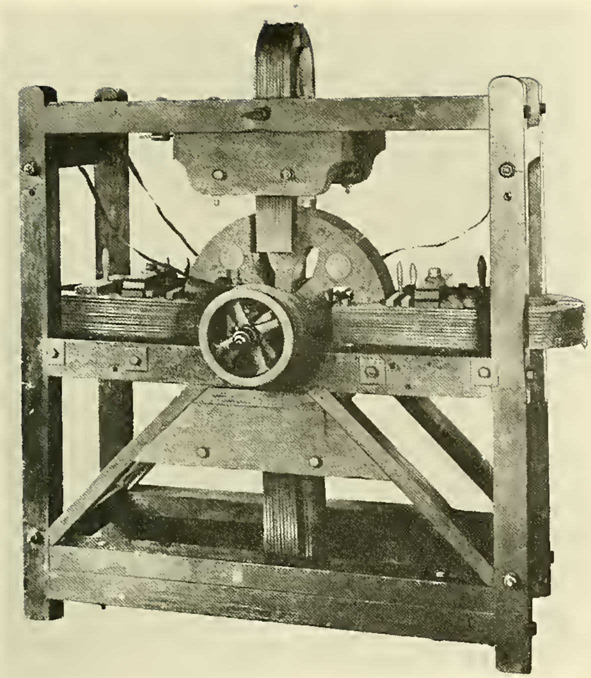
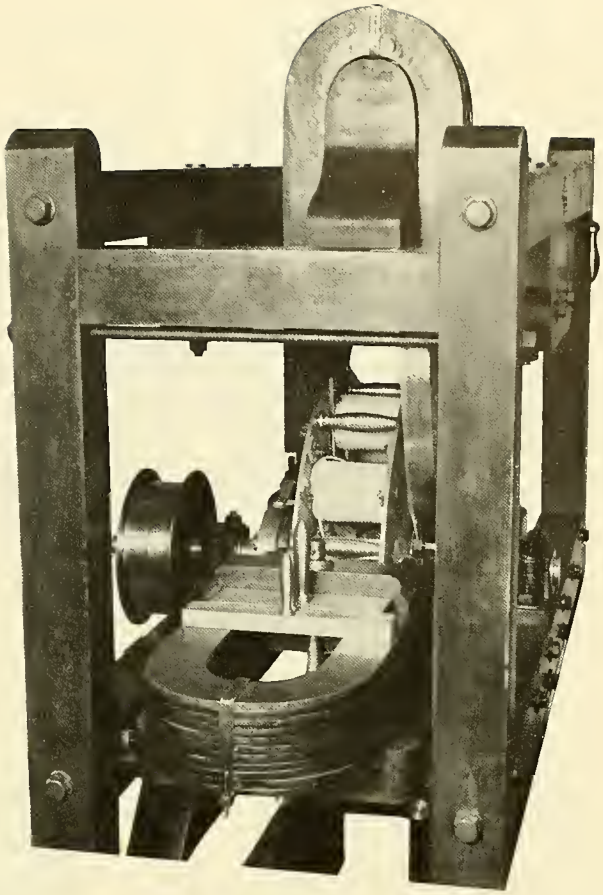


Figure 29.—The first magneto generator designed by Woolrich. It was constructed in 1844. Photos courtesy of Department of Science and Industry, City Museum and Art Gallery, Birmingham, England.



Tyndall, Faraday's associate, could proudly write to the editor of the French scientific publication *Cosmos* that he was the first person to be informed by Faraday of a new application of electricity that "consists of an electric light which is truly splendid and which can be immediately employed for illuminating lighthouses."[35]

Faraday's approval was the result of some demonstrations that Holmes made for Faraday and the Trininty House Light Committee in March 1857 in the latter's experimental "lantern" at Blackwall, near London (fig. 34). It was agreed that a more extensive trial was to be made in a lighthouse, but that Holmes would have to redesign his equipment in order to meet the strict conditions imposed by the Elder Brethren.

The machine used at Blackwall was based on Holmes' patent of the previous year. It had five banks of stationary electromagnets and six rotating disks mounted on a common arbor driven by a 2½-hp. steam engine at 600 r.p.m. There were 6 compound magnets per disk and 24 electromagnets per bank, and the generator was provided with a commutator. The machine was quite large, measuring 5 feet square and 4½ feet high and weighing 2 tons.[36] As a result of the conditions imposed, it now had to be directly coupled to the steam engine, to run at a much lower speed, and to have a sufficiently low electrical output so that it would not be dangerous to the personnel using the equipment. It seems quite

[35] *Cosmos*, 1857, vol. 10, pp. 535–536. See also *Mechanics Magazine*, 1849, vol. 51, pp. 271–272.

[36] F. H. Holmes, "On Magneto-Electricity, and its Application to Lighthouse Purposes," *Journal of the Society of Arts*, 1863, vol. 12, pp. 39–43; James N. Douglass, "The Electric Light Applied to Lighthouse Illumination," *Minutes of Proceedings of the Institution of Civil Engineers*, 1879, vol. 57, pp. 77–165; Gustave Richard, "L'Eclairage électrique des côtes d'Angleterre et d'Australie," *La Lumère électrique*, 1882, vol. 7, pp. 294–300, 327–329, 341–345, 410–414, 460–464, 480–484.

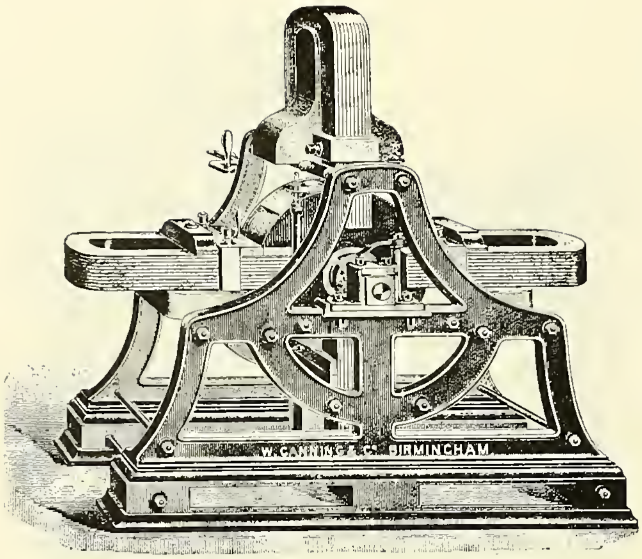


Figure 30.—Woolrich's second magneto generator, made in 1851. From W. H. Carbutt, "Early Electro-Plating Machines," *The Metal Industry*, new ser., February 1914, vol. 12, p. 61.

probable that a good part of Holmes' later difficulties stemmed directly from these restrictions.

Holmes sought to meet the requirements imposed by Trinity House by reversing the role of the permanent magnets and the electromagnets, and by increasing the strength of the magnetic field between the two. He filed for a patent on the revised form of his generator in 1857 (fig. 35).[37] In the new version, two disks bearing the electromagnets were rotated between three banks of stationary permanent magnets. The steam engine was shown in the patent drawing as directly coupled to the generator. The number of permanent magnets was increased from 6 per disk to 20 per bank and the coils from 24 per bank to 80 per disk. The air gap between the electromagnets and the permanent magnets was considerably reduced.

Two machines of the preceding design were tried at the relatively new South Foreland lighthouse on the eastern end of the Straits of Dover. They were about twice as large as those used in the preliminary trials at Blackwall, each being 9¼ feet wide, 5½ feet deep, 9 feet 6 inches high, and weighing 5¼ tons. Each generator was coupled directly to a 3-hp. steam engine that drove it at the maximum permissible speed of 90 r.p.m. A Duboscq regulator maintained the carbons of the electric arc at the proper distance.

The trials began on December 8, 1858, but results were unsatisfactory and they were discontinued; they were started again in March 1859 and continued until the early months of 1860. The arc was apt to go out several times during a night, so that an extra attendant was required just to watch it, but the light could be started again at a touch. After Faraday examined the arc in April 1859 he declared that "Holmes has practically established the fitness and sufficiency of the magneto-electric light for lighthouse purposes."[38] Faraday recommended that Holmes' system be permanently installed and tried under actual operating conditions in a lighthouse for a much longer period of time. Also, he reported publicly on the results of Holmes' system in a lecture given in March 1860 before the Royal Institution, again declaring the result of the experiment to be successful.[39] The point source proved to be admirably adapted to the Fresnel lens system, and the arc light that was so glaring proved to be visible at greater distances than an oil flame. But there was still the problem that had to be faced with all new inventions: whether the initial capital investment might prove to be too great and whether the equipment could be economically maintained. No final decision on its use had been made, for there was the "matter of expense and some other circumstances to be considered."

In the meantime Holmes had devised a regulator similar to that of Serrin. The Holmes system was exhibited in the lighthouse at Dungeness (fig. 36) at the western end of the Straits of Dover in February 1862,[40] but it was not permanently installed until June 6, 1862, because three more men had to be added to the personnel at the lighthouse and it was difficult to obtain competent keepers. The machinery used was the same as that installed at South Foreland.

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[37] British patent 2628 (April 14, 1858).

[38] *Electrician*, London, 1862, vol. 3, p. 67; 1863, vol. 3, p. 288; vol. 4, pp. 78–79. See also Holmes, *op. cit.* (footnote 36) and Richard, *op. cit.* (footnote 36).

[39] Michael Faraday, "On Lighthouse Illumination—The Electric Light," *Proceedings of the Royal Society*, 1858–1862, vol. 3, pp. 222–223; *Electrician*, London, 1863, vol. 4, pp. 68, 122–124.

[40] Holmes, *op. cit.* (footnote 36); Richard, *op. cit.* (footnote 36).

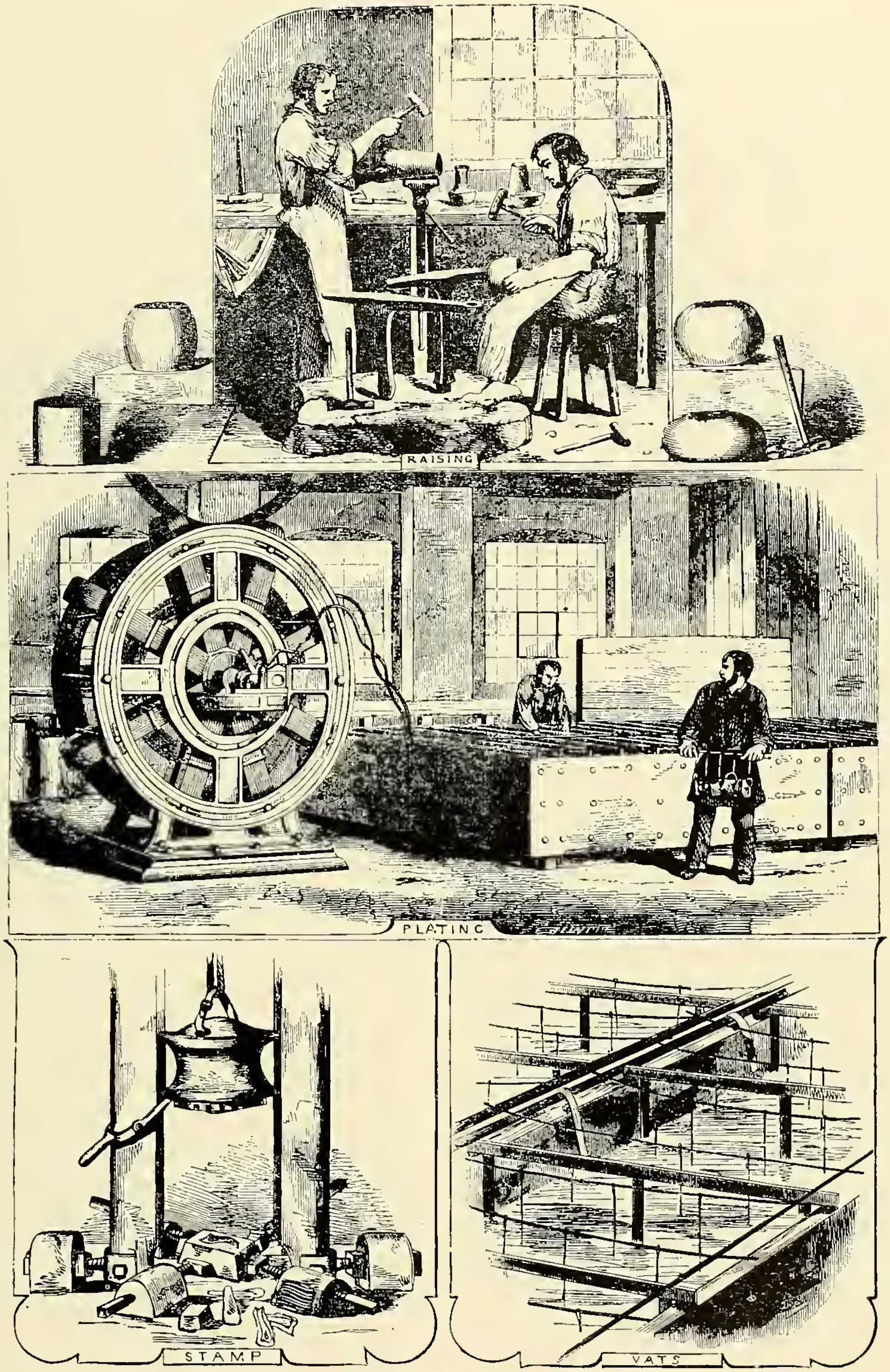

FIGURE 31.—Another form of Woolrich's generator as used in electroplating by Elkington and Company in 1852. From *The Illustrated Exhibitor and Magazine of Art*, 1852, p. 296.

The mean intensity of the beam at the focus was determined to be about 670 candles, while the total intensity was evaluated at about 19,000 candles. The electric light at Dungeness remained in intermittent use for a dozen years, but the combination of an inefficient commutator, frequent mechanical breakdowns, and untrained personnel finally led Trinity House to replace it with an oil light in 1874.

Meanwhile similar efforts made across the Channel in France proved more successful. These attempts were begun by Florise Nollet, professor of physics at the Ecole Militaire in Brussels and a descendant of Abbé Nollet, the famous 18th-century electrical demonstrator. In 1849 Florise Nollet added to his many inventions a version of the Saxton magneto that could be used either to produce hydrogen and oxygen for a Drummond light by the electrolysis of water or to heat a thin carbon rod to incandescence in a vacuum.[41] He then proceeded to design a multiple disk armature generator (fig. 37) which, like Holmes' generator, was basically similar to that of the Woolrich machine.[42]

Nollet's magneto had not yet been constructed when he died in 1853, but his specifications then were being considered by a company that called itself the Electric Power Corporation, with headquarters in Genoa. That company obtained the drawings of Nollet's proposed generator and sought to exploit it in a kind of perpetual motion project. The generator would be used to electrolyze water, and the resulting gases would be used in turn to produce more electricity in a Grove gas battery. After inveigling money out of quite a few prominent people, including Napoleon III, and starting to build six machines according to Nollet's plans, the company was exposed as a fraud.[43] Holmes was one of those called in to recommend a possible use for the abandoned magnetoelectric machines, and it was at this time he suggested they be utilized for arc lights.

Nollet's patent was sold towards the end of 1855, and the Société l'Alliance was formed with Auguste Berlioz as director and with Joseph van Malderen, who had been a coworker of Nollet's, as chief engineer. The new company redesigned Nollet's generator (fig. 38) and sought to place it in commercial use.[44] The first attempt was made in 1856 at the illuminating gas plant located at the Hôtel des Invalides, where the generator was used to provide hydrogen and oxygen by means of electrolysis.[45] This generator was formed of six banks of permanent magnets, with eight magnets radially arranged in each bank, and with the open ends of the magnets pointing towards the axis. There were five disk armatures that rotated between the banks of the permanent magnets (fig. 39). The 16 coils on each disk were connected in series, and the disks could be connected to give either high current or high voltage. In spite of the new company's efforts, the generator was not very successful and no further commercial applications were tried for several years.

An effort was made about this time to obtain some theoretical understanding of the Alliance machines. F. P. Le Roux studied the variation of the current with the external resistance, the variation of voltage with the speed, and the efficiency of an Alliance machine at the Conservatoire des Arts et Métiers in Paris (fig. 40).[46] He found that some two-thirds of the energy from the engine driving the generator was lost internally in the generator. In addition to recommending certain values for the resistance of the generator, he also pointed out that much energy was lost through the production of sparks by the commutator. At the suggestion of Professor Masson, the commutator was removed from the Alliance generator and the efficiency was found to be much greater.[47] Instead of direct current, the generators

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[41] British patent 13302 (October 24, 1850); *Mechanics Magazine*, 1851, vol. 54, pp. 358, 362–364, 410–411.

[42] French patent 11649 (April 26, 1851; addition, April 24, 1852); British patents 14197 (July 6, 1852) and 1587 (July 1, 1853).

[43] *L'Electricité*, 1881, vol. 4, p. 154.

[44] Frank Geraldy, "Les Eclairages électriques à Paris, système de l'Alliance," *La Lumière électrique*, 1880, vol. 2, pp. 259–262. It seems possible that the Compagnie l'Alliance was formed at a later date; Rittershaus mentions 1859 in his article "Zur Geschichte der Dynamo-Maschine" in *Der Civilingenieur*, 1893, neue Folge, vol. 39, p. 350. British patent 2987 (December 2, 1857); French patent 21590, (July 10, 1858; additions, March 14 and December 17, 1859, August 9, 1865, and December 7, 1866).

[45] F. P. Le Roux, "Mémoire sur les machines magnéto-électriques," *Comptes rendus*, 1856, vol. 43, pp. 802–805; Du Moncel, *op. cit.* (footnote 5), vol. 1, pp. 361–364; *L'Année scientifique*, 1858, vol. 3, pp. 80–84.

[46] F. P. Le Roux, "Etudes sur les machines magnéto-électriques," *Bibliothèque Universelle de Genève, Archives des sciences physiques et naturelles*, 1856, vol. 33, pp. 198–213.

[47] Théodose du Moncel, *L'Eclairage électrique*, Paris, 1879, ed 2, p. 59. E. Allard (in *Les Phares: Histoire, construction, éclairage*, Paris, 1889) says Van Malderen suppressed the commutator.

Plan in Section
FIG. 1.

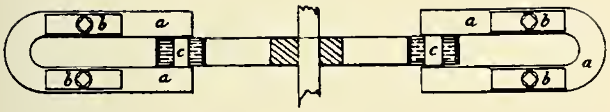
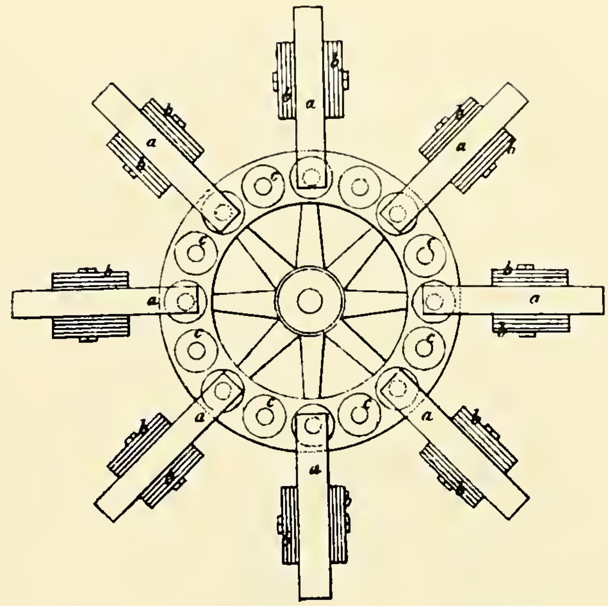


Figure 32.—Patent drawing of Millward's magneto generator, 1851. From British patent specification 13536, February 28, 1851.

Side View
FIG 2



were redesigned for the production of alternating current: one end of the coils on each armature was connected to the axis and the other was connected to an insulated sleeve on it (fig. 41). It was found that a greater amount of current was produced if the resistance of the coils were reduced by winding more turns in parallel on each of the 16 spools on the armature. Preliminary results from the new design were so encouraging that the first 5-disk machine constructed since 1856 was demonstrated at the Hôtel des Invalides in the early spring of 1859.[48] Unlike Holmes' constant experimentation, no further changes in the design of the Alliance machine were made. The only modifications were in the number of disks in the machine, with six seeming to have been the largest practical number on a single arbor, although Jamin and Roger apparently used a 9-disk machine in 1868.

The Société l'Alliance was sufficiently confident of its redesigned machine to consider public demonstrations, and Berlioz was very energetic in seeing that proper occasions were found. In the late fall of 1860 a combination of the Serrin regulator and the Alliance machine was tried on the Dauphin's steam frigate,[49] and it proved successful "in spite of the size of the equipment." In the spring of 1861 two 6-disk machines driven by a 4-hp. steam engine were used for public illumination of the Arc de Triomphe at the Place du Carrousel; other demonstrations were carried out at the Place du Palais Royal early in the summer, and civil authorities tested but rejected the light for street illumination.[50] In the following year a 4-disk machine shown at the London Exhibition of 1862 produced an arc light of 125 Carcel units mean intensity when driven by a 1½-hp. steam engine at 300 r.p.m. The Société l'Alliance was awarded a medal for that performance.[51]

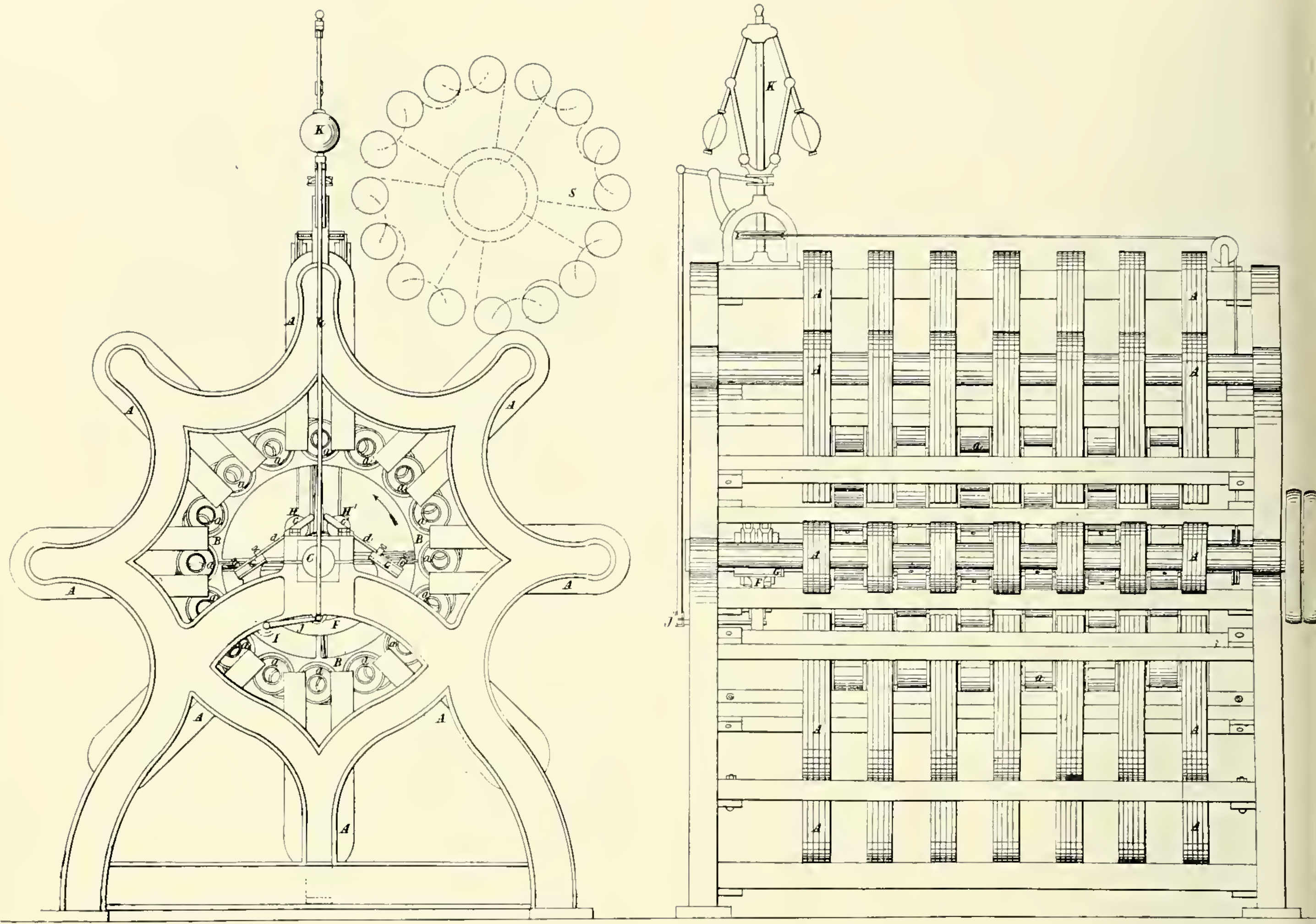
When combined with the Serrin arc light (fig. 42), the new Alliance generator proved it could produce

[48] *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1859, vol. 6, p. 189; Du Moncel, *op. cit.* (footnote 5), vol. 4, pp. 39–47; vol. 5, pp. 102–104.

[49] *Cosmos*, 1860, vol. 17, p. 427.

[50] *Annales télégraphiques*, 1861, vol. 4, p. 84; 1862, vol. 5, pp. 505–520; *Bulletin de la Société pour l'Encouragement de l'Industrie Nationale*, 1861, vol. 8, pp. 181–182; *Cosmos*, 1861, vol. 18, pp. 197–200; vol. 19, p. 29; *L'Illustration*, 1861, vol. 37, p. 347; *L'Année scientifique*, 1862, vol. 6, pp. 48–52.

[51] *Dinglers polytechnisches Journal*, 1863, vol. 167, pp. 104–111; *Cosmos*, 1862, vol. 20, pp. 686–694; Daniel K. Clark, *The Exhibited Machinery of 1862*, London, 1864, pp. 288–289.



relatively steady illumination with few breakdowns, but it could be used only where unusual conditions justified its high initial cost. Such conditions were to be found in the French lighthouse service, where it was to have more success than Holmes' machine had had in England.

When the arc light first appeared in the theater in 1848, the French administration of public works, which was entrusted with lighthouse service, began to consider the possibility of using this new form of illumination. At first, that body experimented with running the arc light by means of chemical cells, but when the experiments of Faraday and Holmes were brought to its attention in 1857, the feasibility of the magnetoelectric machine was considered. However, no action was taken until the director of the French lighthouse administration, Léonce Reynaud, and his chief engineer, E. Allard, visited Holmes' installation at South Foreland in April 1859. After hearing of the increased efficiency of the commutatorless Alliance machine, Reynaud decided to obtain one for experimentation. By the fall of 1859 the Alliance machine was being tested for possible use in the French lighthouse system. After careful study, Reynaud submitted an extensive report early in 1863 on its possible brightness, the distance from which it could be seen, and the economic advantages of its use in a lighthouse. He found that a 6-disk machine produced an arc of 180 to 190 Carcel units mean intensity when driven by a 2-hp. steam engine, and

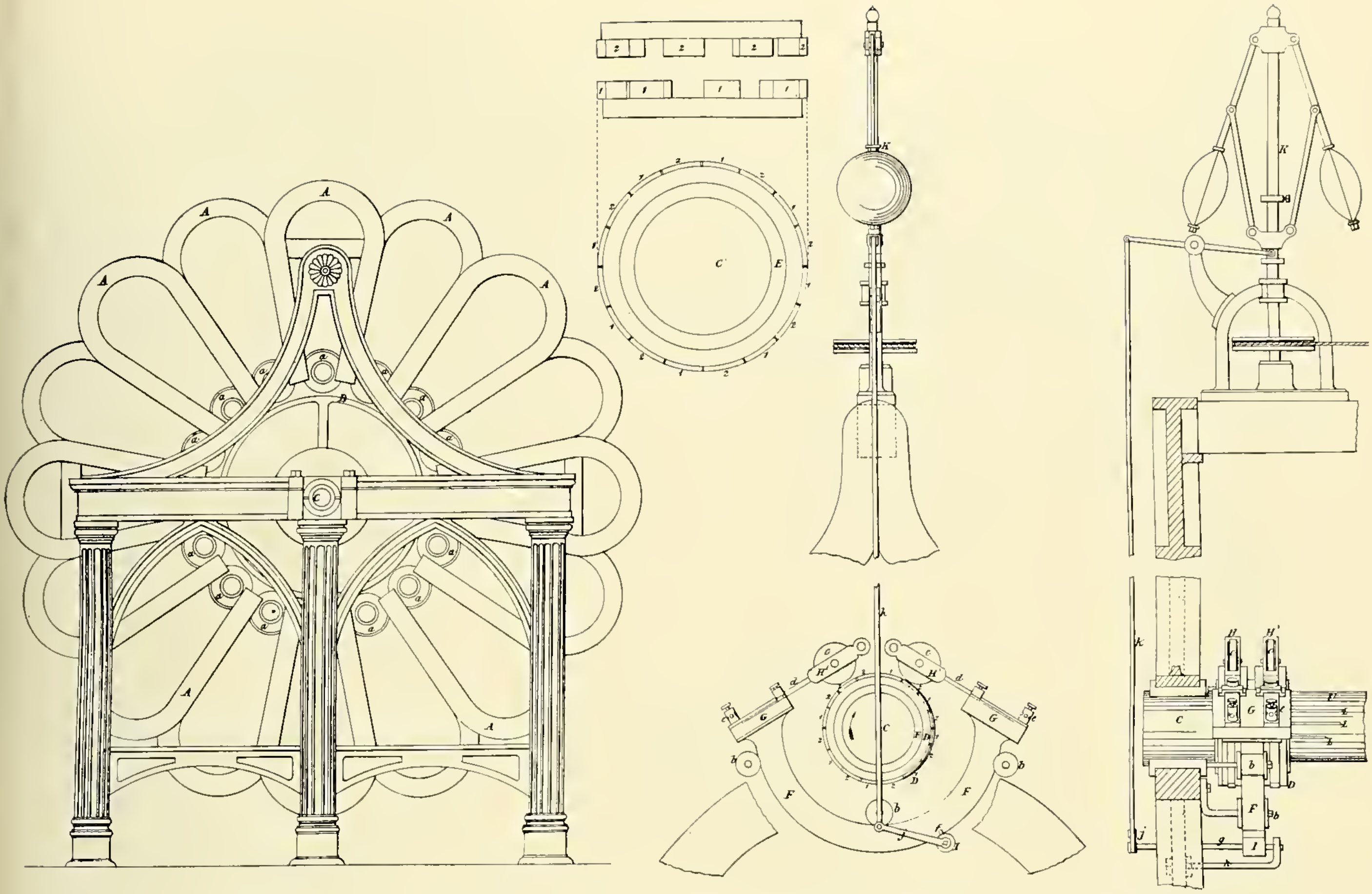


FIGURE 33.—*On facing page and above:* Patent drawings of Holmes' magneto generator of 1856. Note the current collectors and the speed regulator on the machine. From British patent specification 573, March 7, 1856.

he recommended that the government purchase a pair of Alliance machines for actual trial in a lighthouse of the first-order.[52]

[52] *L'Illustration*, 1863, vol. 42, p. 190; J. H. Gladstone, "Lighthouse Illumination by Magneto-Electricity," *Quarterly Journal of Science*, 1864, vol. 1, pp. 70–75; *Cosmos*, 1859, vol. 15, pp. 511–512; Faye, "De l'Application des feux électriques aux phares et à l'illumination à longue portée," *Comptes rendus*, 1861, vol. 52, pp. 375–377, 413–415; Léonce Reynaud, "Rapport sur l'application de la lumière électrique à l'éclairage des phares," *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1863, ser. 2, vol. 10, pp. 496–504. Fontaine (*op. cit.*, footnote 12, p. 352) gives one Carcel unit as 7.4 English candles, and other values of the period ranged between 7.5 and 9.5 candles. The current value of the Carcel unit is 9.6 English standard candles (*Smithsonian Physical Tables*, Washington, 1954, rev. ed. 9, p. 92).

In a short time the Alliance-Serrin combination began to appear in some of the lighthouses along the coast of France. Following Reynaud's report, on July 14, 1863, two 6-disk machines were ordered for Cap de la Hève near the port of Le Havre (figs. 43–45).[53] They had the usual combination of 16 electromagnets in each disk and eight permanent magnets in each of the seven banks of magnets. When the machine was driven by a 2-hp. steam engine at 400 r.p.m. the engineers found that about 190 Carcel units were produced in the arc. The south lighthouse on the cape

[53] *Les Mondes*, 1863, vol. 1, pp. 691–694; *Cosmos*, 1863, vol. 23, p. 115; *L'Illustration*, 1863, vol. 42, p. 190; *L'Année scientifique*, 1864, vol. 8, pp. 63–74.

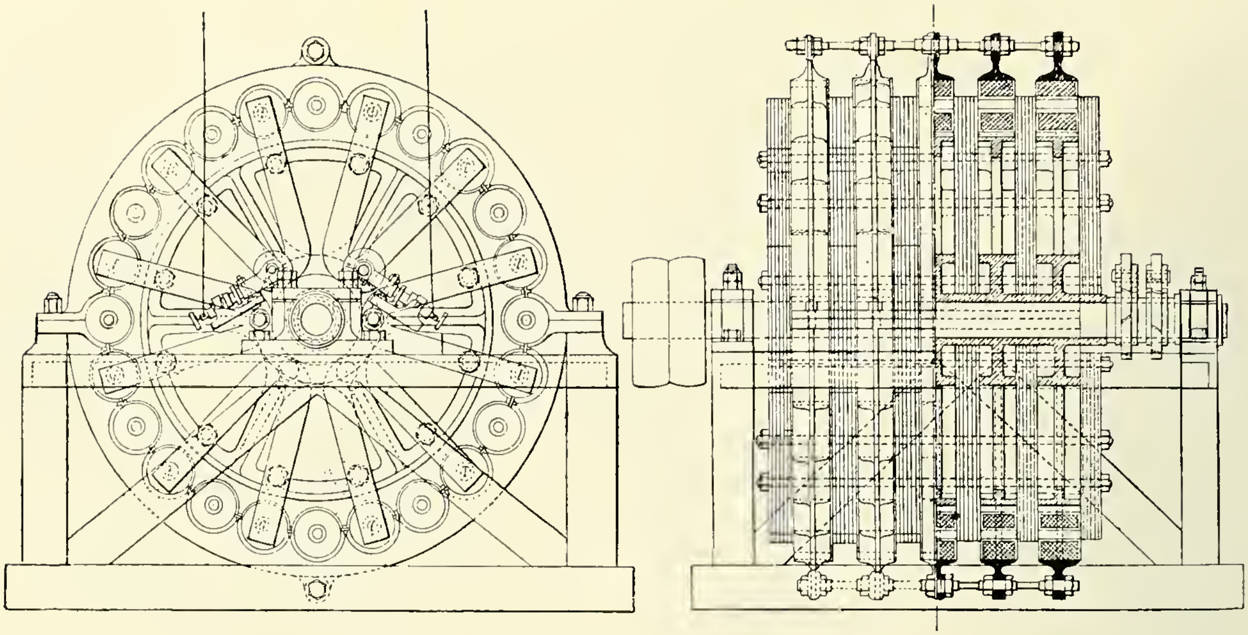


Figure 34.—Holmes' experimental magneto generator that was demonstrated at Blackwall. From *La Lumière électrique*, September 23, 1882, vol. 7, p. 298.

went into operation on December 26, 1863, and the results were so encouraging that a pair of the machines were installed in the north lighthouse in 1865.[54]

Le Roux, in published preliminary engineering reports on the success of the installation at the lighthouses, questioned the reliability of the new system, pointing out that, despite previous hopes, the light from the arc was not much brighter than that from oil; also, Reynaud, in a formal report to the French government, concluded that the two lighthouses were too expensive for ordinary use but were valuable where great brilliance was required.[55] Notwithstanding these objections, another installation was made at Cap Gris Nez, near Calais, in February 1869, and other Alliance installations were made outside France—when the Suez Canal was opened in 1869 a lighthouse using Alliance equipment was set up at Port Said, and two years later a similar installation was made at Odessa, in southern Russia.[56] The brightness of the arc had been increased, and it was now claimed to be 300 Carcel units.

No more French installations were made in the decade following the Franco-Prussian war, but in January 1880 there was a proposal to install electric lighting in all the first-order lighthouses along the coast of France. Palmyra, a city at the mouth of the Gironde River, and Planier, an island in the Mediterranean near Marseilles, each obtained an electric lighthouse in 1881. In the following year the French government made a large appropriation for the installation of 46 electric lighthouses along the coast.[57]

About this time electric lighthouses—but not of the Alliance system—began to appear outside Europe.

[54] *Les Mondes*, 1864, vol. 4, pp. 57–61; A. Guerout, "L'Eclairage électrique du Port du Havre," *La Lumière électrique*, 1881, vol. 4, pp. 132–136; *Cosmos*, 1866, ser. 2, vol. 4, pp. 7–11; *L'Année scientifique*, 1866, vol. 11, pp. 48–56.

[55] F. P. Le Roux, "Les Machines magnéto-électriques françaises et l'application de l'électricité à l'éclairage des phares," *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1867, vol. 14, pp. 677–711, 748–790; Léonce Reynaud, "Expériences comparatives des deux systèmes d'éclairage des phares à l'huile et à la lumière électrique, considérés au point de vue économique," *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1867, vol. 14, pp. 776–779; *Cosmos*, 1866, vol. 4, pp. 7–11.

[56] *Cosmos*, 1870, ser. 3, vol. 6, pp. 103–104; *L'Année scientifique*, 1870–1871, vol. 15, pp. 50–51; "Lighthouse," *Encyclopedia Britannica*, New York, 1911, ed. 11, vol. 16, p. 641.

[57] Allard, *op. cit.* (footnote 47), pp. 325–383; "Note sur quelques objections relatives à l'emploi de la lumière électrique dans les phares," *Annales des ponts et chaussées, mémoires et documents*, 1882, vol. 1, pp. 489–502; A. Guerout, "L'Eclairage électrique des côtes de France," *La Lumière électrique*, 1881, vol. 5, pp. 25–35.

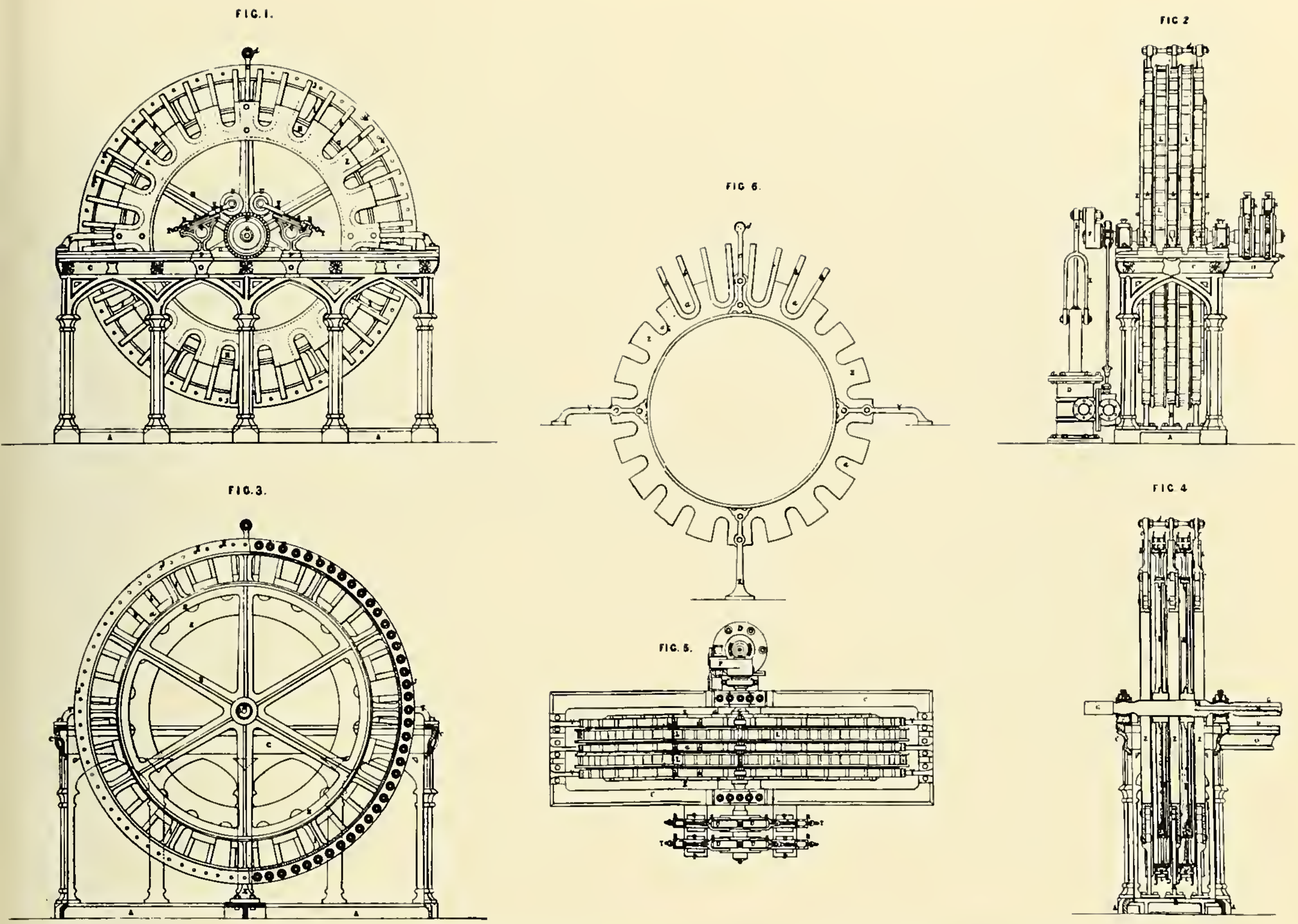


Figure 35.—Patent drawing of Holmes' magneto generator of 1857. The magnets rotated, rather than the armature. From British patent specification 2628, October 14, 1857.

The first one in the New World was set up at Rio de Janeiro in 1882, and Australia obtained one at Macquarie, in the Bay of Sidney, in the same year.[58]

The lighthouse was not the only application to navigation that the persistent Berlioz found for his magneto generator. Prince Napoleon again tried it on his yacht in the spring of 1867, and it proved to be so advantageous for traveling at night and for signaling that, after some further experimentation, it was installed permanently; a frigate of the French navy's Mediterranean fleet and the transatlantic passenger liner *St. Laurent* were equipped with the Alliance system in 1868; and a public demonstration of the magneto generator was tried at the Gare de l'Est and pronounced to be satisfactory.[59]

However, it should not be thought that the Alliance system had replaced chemical cells in public illuminations. The Fêtes des Souverains held by Napoleon III in 1868 in the French capital used chemical cells as the source of power for the 32 Serrin regulators illuminating the Tuileries,[60] and Baron Hausmann

[58] Richard, *op. cit.* (footnote 36); John Hopkinson, "The Electric Lighthouses of Macquarie and of Tino," *Minutes of Proceedings of the Institution of Civil Engineers*, 1886, vol. 87, pp. 243–260.

[59] *Les Mondes*, 1867, vol. 13, pp. 405–406, 492; 1868, vol. 16, pp. 488–494, 594–595, 700–702; vol. 18, pp. 51–52, 130, 325–327, 458–459, 593–594, 637–639; 1869, vol. 19, pp. 238–239; vol. 20, pp. 605; vol. 21, pp. 471–472; 1870, vol. 23, pp. 466–467.

[60] "Eclairage," *La Grande Encyclopédie*, Paris, n.d., vol. 15, pp. 341–346; Defrance, *op. cit.* (footnote 2).

used the same means to enable the laborers to work through the night during his modernization of Paris.[61]

During the 1860's the Alliance machine with a commutator was also tried in other enterprises. An attempt was made to use the generator instead of chemical cells in the telegraph central power station and it, too, was declared a success, although not as complete a one as the attempt made in Prussia, "since France was larger."[62] In 1868, the famous Parisian electroplating firm of Christofle sought to imitate its competitor, the Elkington firm with its English generators, by using the Alliance machine for plating.[63]

Some of the first experiments conducted at the Sorbonne's new physical laboratory in 1868 were concerned with the Alliance machine.[64] J. C. Jamin and G. Roger continued the work of Le Roux and gave experimental proof for the usual assumption that each coil on the disk armature was equivalent to a chemical cell. The output of the generator could then be calculated by applying Ohm's law to a battery of cells, each of which produced a certain voltage and had a certain fixed internal resistance. Jamin and Roger also investigated the relationship between the energy necessary to drive the generator and the heat produced in the external circuit. Some insight into the cost of the electric light can be obtained from their finding that 100 liters of gas must be consumed in the gas engine driving the generator in order to maintain an electric arc at the same intensity as a gas burner using one liter of gas per minute.

Before the Alliance machine gave way before the superior Gramme machine (discussed below), it played a role, although a minor one, in the defense of Paris during the Franco-Prussian War.[65] Arc-light stations were installed in the various forts circling the city, and each was provided with four electricians and with equipment garnered from instrument-makers, telegraph offices, and laboratories. Bunsen cells were used in most of these stations, but the brightest light of all, at the Moulin de la Galette, obtained its power from an Alliance machine. The arc lights were not very effective, but they did help to prevent surprise attack and to discourage sappers during the night.

When Holmes heard of the French commutatorless machines, he sought to produce machines of a similar type. After filing his first patent specification on an alternator in 1867 (fig. 46), he filed two other patents, one in 1868 and one in 1869.[66]

In 1867 Holmes constructed two alternators (fig. 47) for a new lighthouse to be erected on the northeastern coast of England at Souter Point, near Newcastle. Before installation the new units were sent to the Paris exhibition of 1867 where, at first, they failed to work. Seven banks with eight permanent magnets per bank and six disk-armatures with 16 electomagnets per disk constituted the 3-ton machine, which was 6 feet long, 4 feet 4 inches wide, and 5 feet 6 inches high. About 3 hp. was required to drive the machines at 400 r.p.m. and to produce 1,520 cp. Almost four years elapsed before the machines were in use; they were first turned on in January 1871. But the expenses were only half that at Dungeness, and, most important, the lights were constantly in service. Eight years later two similar machines were installed in each of the two lighthouses at South Foreland.[67]

By 1882 there were five electric lighthouses in England and four in France. However, not all of these used the Alliance or the Holmes machines, for serious competition had appeared. The lighthouse at Planier used the more efficient modification of the Alliance machine invented by De Meritens (fig. 48),[68] but a still more serious competitor of the magneto generators was the new dynamo generator. By the time the first lighthouse dynamo was installed, in the channel at Lizard Point in 1878, the dynamo generator already had begun to dominate in the field of electric light.

Before turning to the story of the dynamo, it might be of interest to compare the performance of the two magneto generators, the Alliance and the Holmes

[61] *Journal of the Society of Arts*, 1868, vol. 16, p. 826.

[62] *Les Mondes*, 1867, vol. 15, p. 702.

[63] *Les Mondes*, 1867, vol. 13. pp. 405–406; 1868, vol. 16, p. 177.

[64] Le Roux, *op. cit.* (footnote 87); *Cosmos*, 1868, vol. 2, pp 6–7; Jules Jamin and Gustav Roger, "Sur les Machines magnéto-électriques," *Comptes rendus*, 1868, vol. 66, pp. 1100–1104, and "Sur les Lois de l'induction," *Comptes rendus*, 1868, vol. 66, pp. 1250–1252.

[65] *L'Année scientifique*, 1874, vol. 18, pp. 430–434; *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 1870, vol. 17, pp. 659–665.

[66] British patents 2307 (February 10, 1868), 2060 (December 23, 1868), and 1744 (December 3, 1869).

[67] See Douglass, *op. cit.* (footnote 36) and Richard, *op. cit.* (footnote 36).

[68] French patent 123766 (April 10, 1878; additions, May 8 and June 26, 1878); Du Moncel, *op. cit.* (footnote 47), pp. 85–88; *Engineering*, 1879, vol. 28, pp. 372–373.

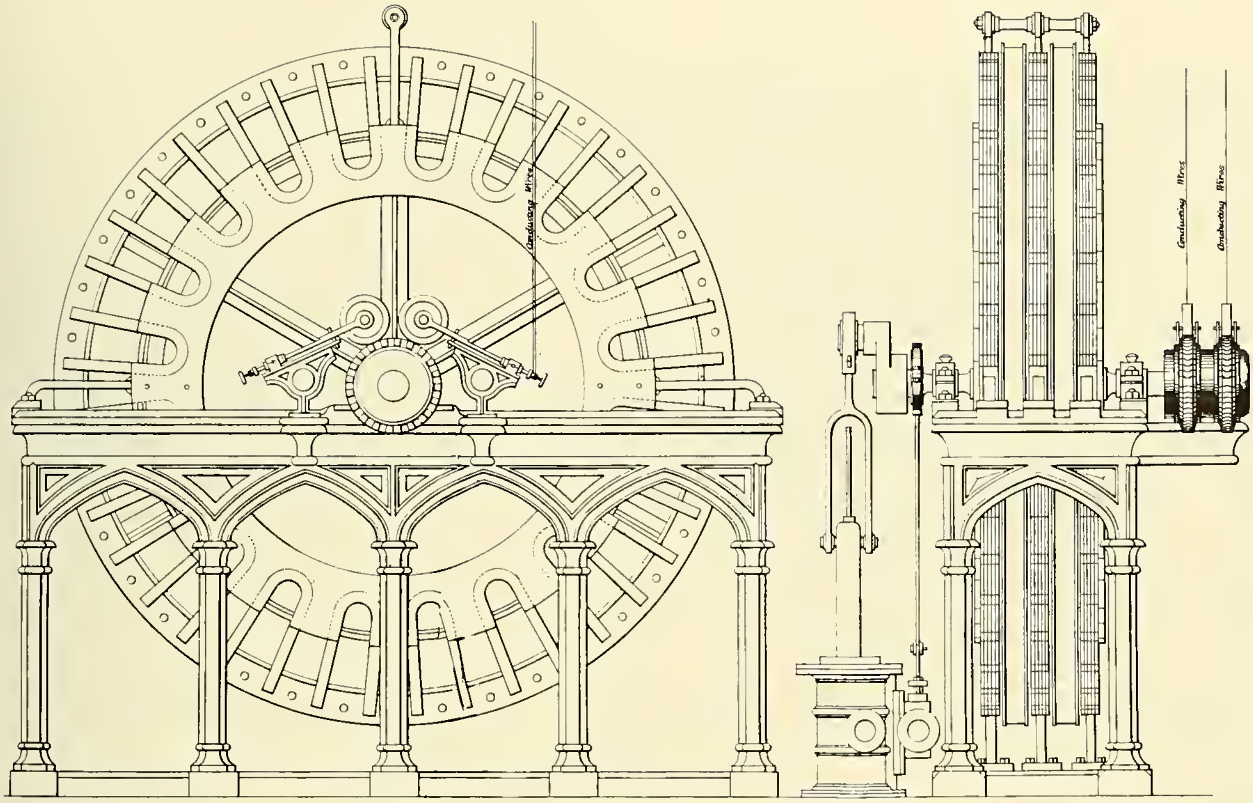


Figure 36.—Side and end elevations of Holmes' magneto generator that was installed at Dungeness. From *Minutes of Proceedings of the Institution of Civil Engineers*, 1878–1879, vol. 57, pl. 5.

machines, with that of the dynamo generator. At the time the magnetoelectric machines were in commercial use, the system of practical electrical units had not been worked out; consequently, what little information is available is not always meaningful, but at least one can obtain some sense of the relative merits of the equipment.

One method of measuring the output of an electrical machine was to determine it in terms of the chemical cell. In tests made in 1862 it was shown that a 4-disk Alliance machine was equivalent to 64 Bunsen cells. [69] The tests that Jamin and Roger performed in 1863 showed that a 6-disk Alliance machine produced a voltage equal to that of 226 Bunsen cells when the disks were connected in series and, as might be anticipated, a voltage equal to 38 Bunsen cells when the disks were connected in parallel.[70]

Also, one could obtain a crude comparison of the efficiency of various machines by determining the amount of light that each machine produced per unit horsepower. However, these comparative estimates are necessarily nominal because the candlepower of the arc and the horsepower necessary to produce the candlepower were not measured together, at least until 1880; consequently, such estimates should be considered with caution. Another factor that casts doubt on these estimates is that the figures were used to sell the generators rather than to represent scientific measurements. Nevertheless, the figures are indicative of the order of magnitude, and they became

[69] *Cosmos*, 1862, vol. 20, pp. 686–694.

[70] Jamin and Roger, *op. cit.* (footnote 64).

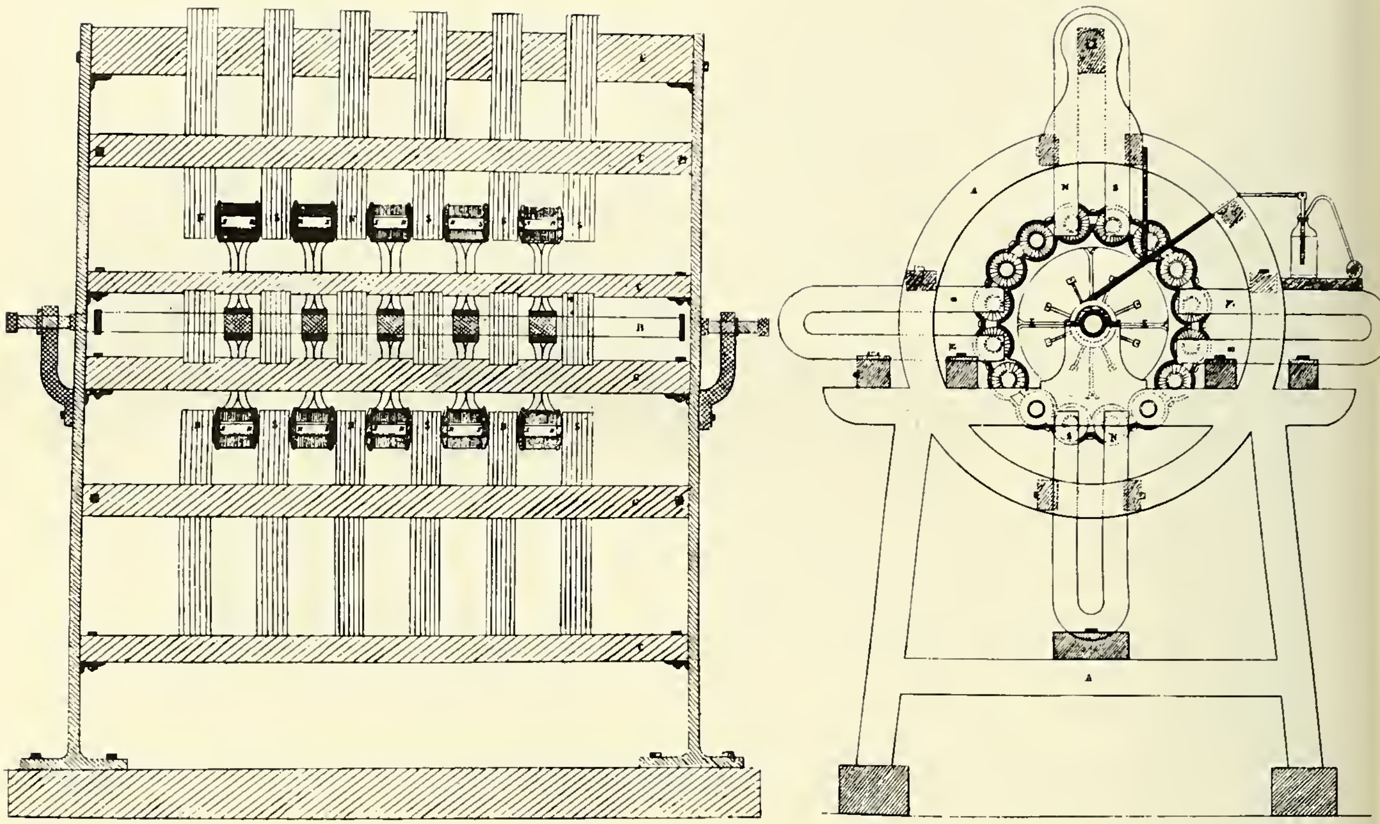


Figure 37.—*On facing page and above:* Patent drawings of Nollet machine, 1853. From British patent specification 1587, July 1, 1853.

more accurate as the 1880's were approached. Such figures for the Alliance machine during the decade of the 1860's are as follows:

Year	*Number disks*	*Carcel units per hp.*	*Reference*
1860	6	55–65	*Cosmos,* 1860, vol. 17, p. 427.
1861	6	65	*Cosmos,* 1861, vol. 18, pp. 197–200, 646–647.
1862	4	85	*Annales Telegraphiques,* 1862, vol. 5, pp. 505–520.
1863	6	90–95	Reynaud, *op. cit.* (footnote 52).
1866	6	65	Le Roux, *op. cit.* (footnote 55).

Of the preceding figures, probably only those for 1866 are adequate for the purpose. (An analogous comparison of electroplating generators can be worked out by determining how much metal was deposited for unit time.)

Similar measurements performed in the middle of the following decade led to the first careful comparison of the older magnetoelectric machines and the newer dynamoelectric machines. (That such a test first occurred a decade after the enunciation of the principle of self-excitation serves to demonstrate the slowness with which the commercial electric generator developed.) Holmes had suggested the use of the new kind of generator early in 1869, and had even constructed a pair for the South Foreland lighthouse that year.[71] However, despite the fact that the dynamos produced a much brighter light than Holmes' magneto generators in the tests, the Elder Brethren of Trinity House held it to be wiser to choose

[71] Douglass, *op. cit.* (footnote 36).

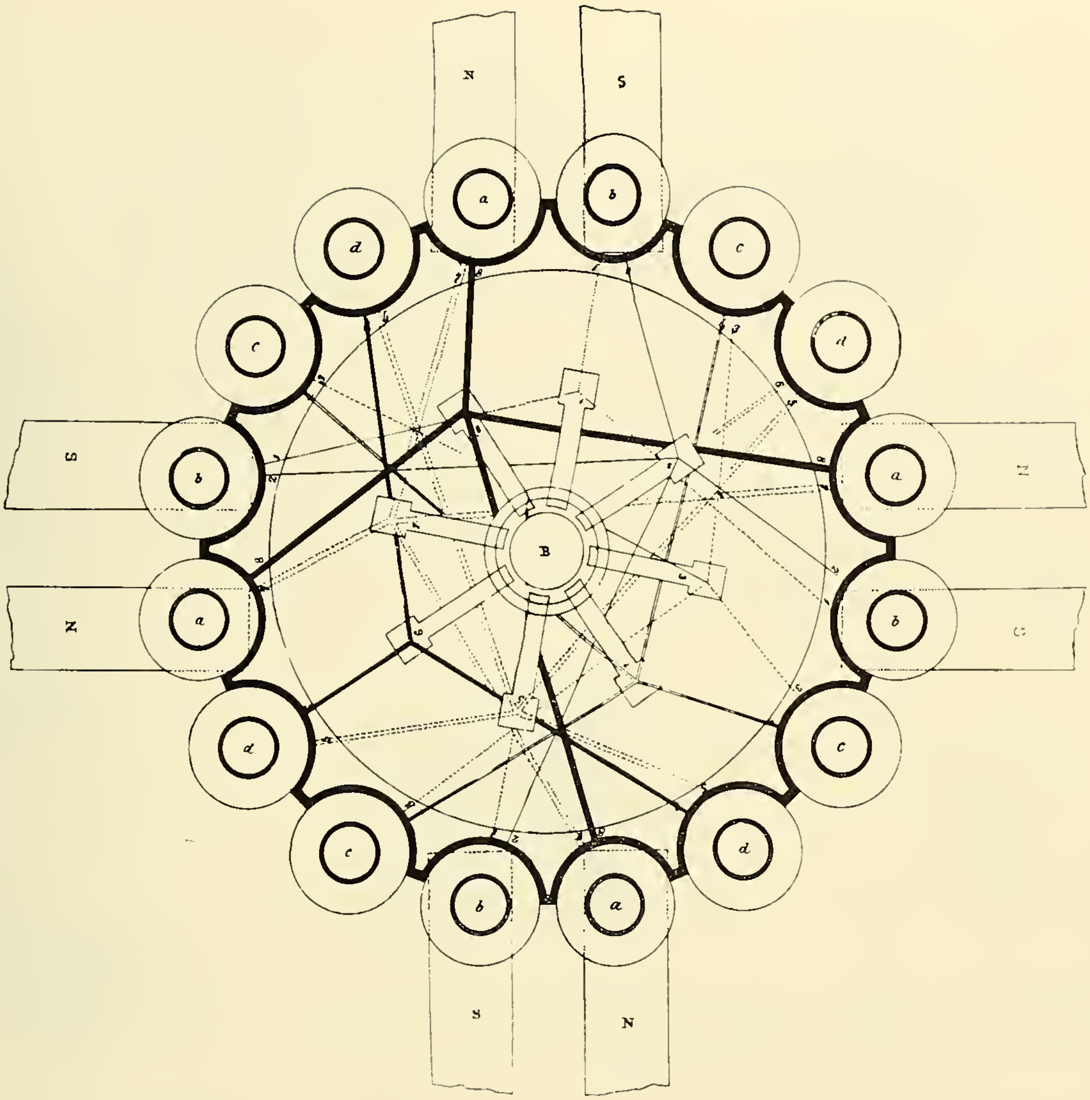


Table 1.—*Results of the trial competition of generators in winter of* 1876–1877.

Generator	Length	Breadth	Height	Cost (£)	Weight (tons)	H.p. absorbed	R.p.m.	Light (candles)		Candles/h.p.		Order of merit
								Condensed	Diffused	Condensed	Diffused	
Holmes	4′ 11″	4′ 4″	5′ 2″	750	2½	3. 2	400	1520	1520	480	480	6
Alliance	4′ 4″	4′ 6″	4′ 10″	500	1¾	3. 6	400	1950	1950	540	540	5
Gramme, no. 1	2′ 7″	2′ 7″	4′ 1″	300	1¼	5. 3	420	6660	4000	1260	760	4
Gramme, no. 2	2′ 7″	2′ 7″	4′ 1″	300	1¼	5. 7	420	6660	4000	1260	760	4
Siemens, large	3′ 9″	2′ 5″	1′ 2″	265	½	9. 8	480	14820	8930	1510	910	3
Siemens, small, no. 58	2′ 2″	2′ 5″	10″	75	⅙	3. 5	850	5540	3340	1580	950	2
Siemens, small, no. 68	2′ 2″	2′ 5″	10″	75	⅙	3. 3	850	6860	4140	2080	1250	1

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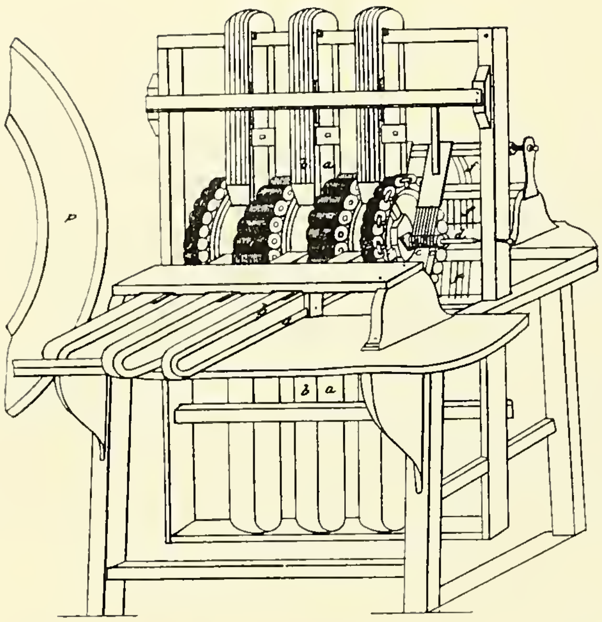
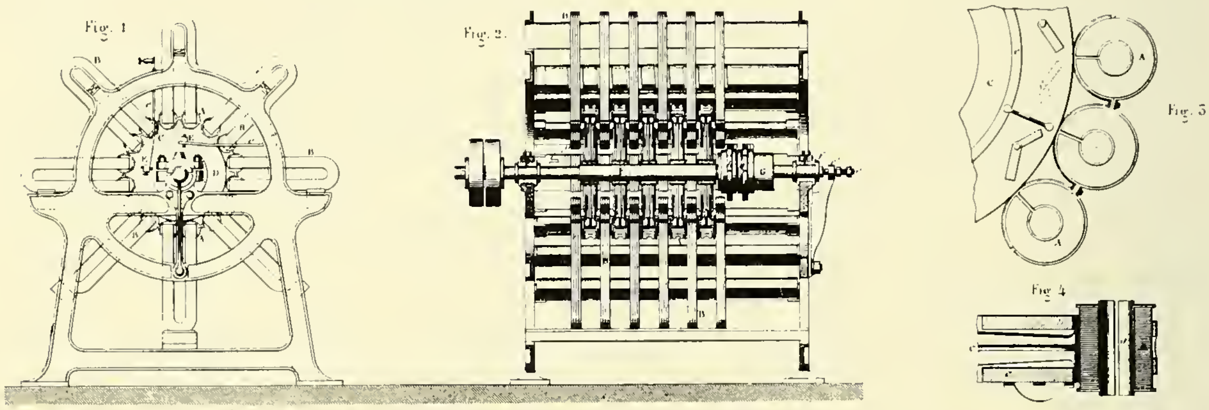


Figure 38.—One of the first forms of the Alliance machine. Note the brushlike current collectors. Reproduced, with permission of the publisher, from O. Mahr, *Die Entstehung der Dynamomaschine* (vol. 5 of *Geschichtliche Einzeldarstellungen aus der Elektrotechnik*, Berlin, J. Springer, 1941), p. 89, fig. 61.



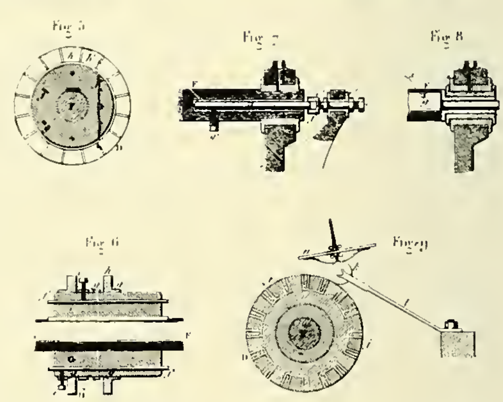


Figure 39.—The usual form of the Alliance generator as provided with a commutator. From *Annales telegraphiques*, 1862, vol. 5, pl. 5.

the magneto generators, which had already been found reliable.

The attention of Trinity House was again brought to the new machines in 1876 by an exhibition of the Loan Collection of Scientific Apparatus held at South Kensington. There one could see the dynamos of Gramme and Siemens together with the magnetos of the Société l'Alliance and of Holmes. Trinity House thereupon invited the manufacturers to a trial competition to determine the kind of apparatus best suited for the new lighthouse at Lizard Point. The tests were held at South Foreland during the winter of 1876–1877 under the joint supervision of Professor Tyndall, successor to Faraday as scientific adviser to Trinity House, and James N. Douglass, chief engineer of Trinity House.

The results of these tests (see table 1) showed the new dynamo to be far superior to the magneto generator.[72] Of the two dynamos, the Siemens

[72] John Tyndall, "Report on Electric Illumination," *Engineering*, 1877, vol. 24, p. 303; James N. Douglass, "Report on Electric Illumination," *Engineering*, 1877, vol. 24, pp. 333, 351; Richard Higgs and John Brittle, "Some Recent Improvements in Dynamo-Electric Apparatus," *Minutes of Proceedings of the Institution of Civil Engineers*, 1878, vol. 52, pp. 36–98.

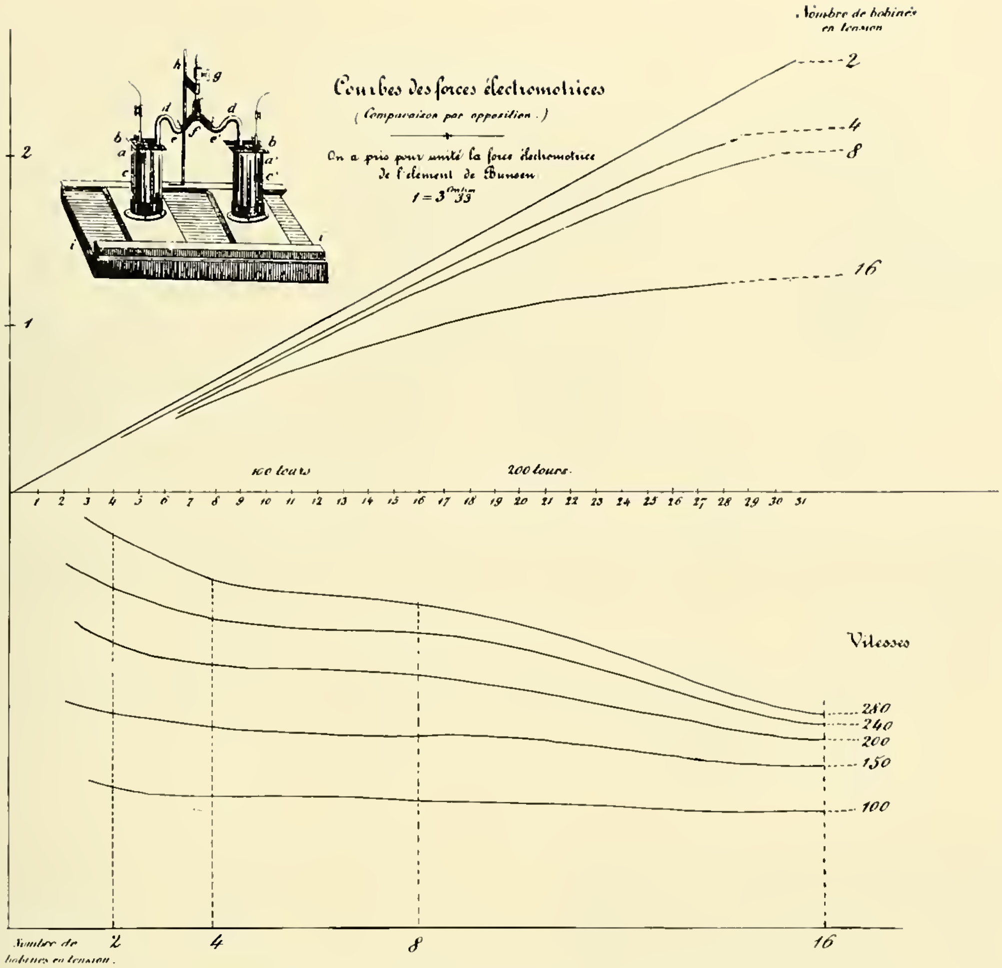


Figure 40.—Results of Le Roux's study of the relation between the speed of rotation and the voltage (open circuit) for varying numbers of coils on the armature of an Alliance generator. From F. P. Le Roux, "Etudes sur les machines magnéto-électriques," *Archives des sciences physiques et naturelles*, 1856, vol. 33, figs. 1–3 (following p. 263).

proved itself to be electrically and mechanically superior. In addition to being cheaper as well as less bulky, the Siemens dynamo could produce twice as many candles per horsepower as its best magneto competitor. By examining the tabulation, the respective proportions of the Holmes magneto and the Siemens dynamo can be seen to be as follows: bulk, 114 to 1; weight, 28 to 1; total light produced, 1 to 5; light produced per horsepower, 1 to 4; cost per unit of light, 9 to 1. Obviously, the magneto generator could not compete with the new dynamo generator, and Trinity House decided to install the Siemens dynamo instead of the Holmes generator at Lizard Point.

Hippolyte Fontaine, of the Gramme firm, protested to the editor of *Engineering* that the trials were unfair, since the Gramme machine used in the tests was the 1874 model rather than the new *type d'atelier* (actually, the company had refused to submit a model). Fontaine quoted Tresca—who had tested the new Gramme machine—as having found that 2 hp. produced 7,000 candles. Fontaine further went on to describe

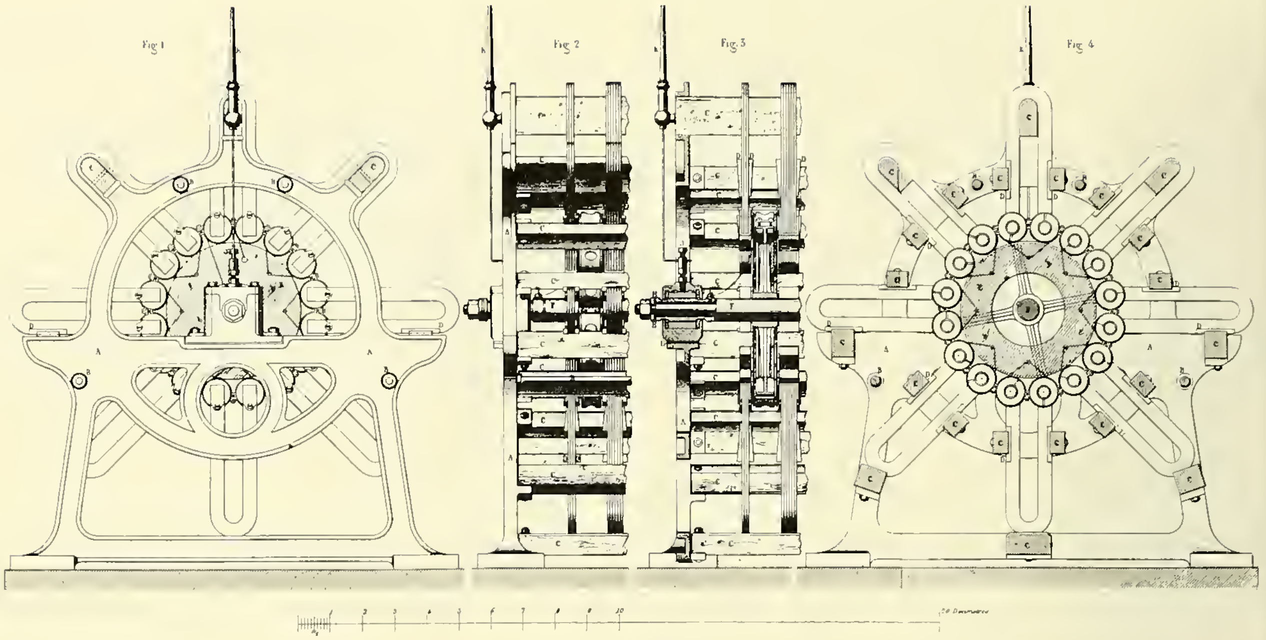
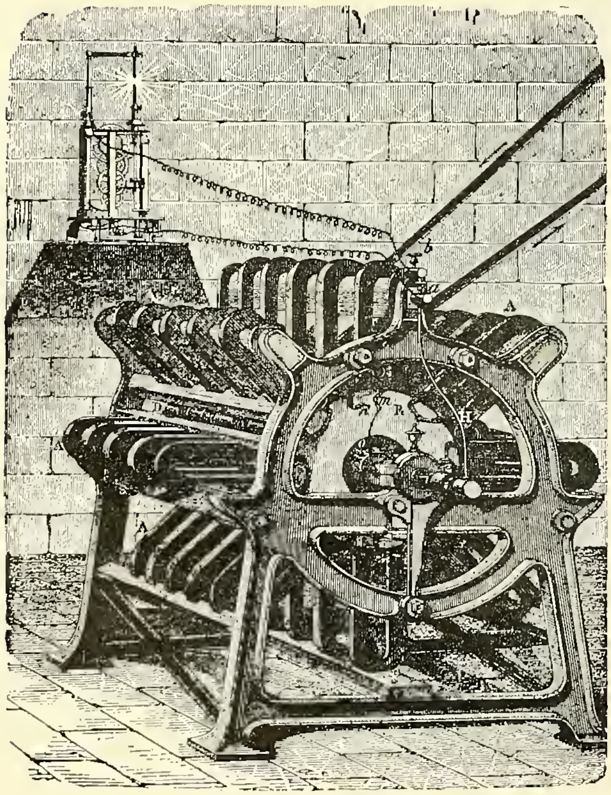


Figure 41.—Details of Alliance magneto generator, without commutator. From *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, ser. 2, 1867, vol. 14, pl. 370 (facing p. 804).



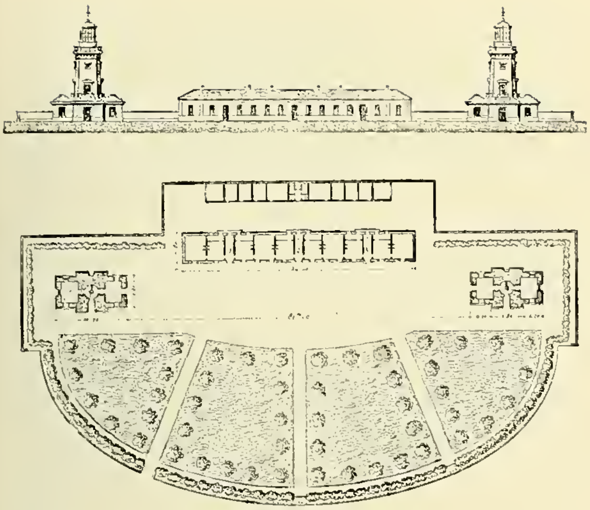
the machine as costing £100, as being 2 feet long, 1 foot 2 inches wide, and 2 feet high, and as weighing 360 pounds.[73] Actually, the results cited were overly sanguine on Fontaine's part—Tresca found that the 300-Carcel-unit dynamo required 2.8 hp. and the 1,850-Carcel-unit machine required 7.7 hp. This would result in 107 and 240 Carcel units per horsepower, which still seems quite high.

The central testing depot of the French lighthouse administration carried out similar tests of the Alliance, De Meritens, and Gramme machines during the years 1880–1882.[74] As can be seen from the following

[73] *Engineering*, 1877, vol. 24, p. 322 (see also letter from Charles Ball, p. 348); Henri E. Tresca, "Compte rendu des expériences faites pour la détermination du travail dépensé par les machines magnéto-électrique de M. Gramme, employées pour produire de la lumière dans les ateliers de MM. Sautter et Lemonnier," *Comptes rendus*, 1876, vol. 82, pp. 299–305.

[74] Allard, *op. cit.* (footnote 47), pp. 339–348.

Figure 42.—Alliance generator being used to drive an arc light. From *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, ser. 2, 1867, vol. 14, fig. 16 (p. 692).



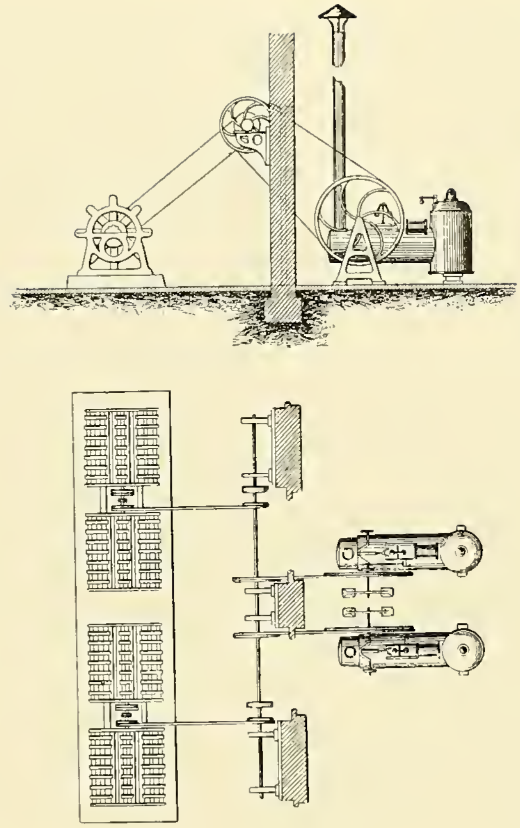


FIGURE 43.—*Above,* Double lighthouse at Cap de la Hève outside the harbor of Le Havre. *At right,* Arrangement of the steam engines and the Alliance generators in the south lighthouse. From E. Allard, *Phares et balises,* vol. 5 of *Les Travaux publics de la France,* L. Reynaud, ed., Paris, 1883, pp. 59, 109.

tabulation, the Alliance generator produced approximately the same carcels per horsepower as it had in the South Foreland tests, the Gramme dynamo had improved somewhat, and the De Meritens magneto, surprisingly enough, proved to be about as efficient as the Gramme machine:

Generator	*R.p.m.*	*Mechanical hp. absorbed*	*Mean spherical intensity (Carcels)*	
			Total	*Per hp.*
Alliance	450	4.6	275	60
Gramme, large	550	11.5	1010	88
Gramme, small	600	5.5	493	91
Gramme, improved small	680	4.2	342	81
De Meritens, low speed	431	5.8	537	93
De Meritens, high speed	827	11.9	1015	85

From these figures and from the results of other tests that are mentioned below, it can readily be seen that the dynamo was a great advance over the older machines in terms of bulk, weight, candles produced per horsepower, and initial cost. Despite such advantages, the magnetoelectric machine was not displaced by the dynamoelectric machine until the end of the 1870's, and even then not completely.

The changes that made possible a mechanically and electrically more efficient generator were introduced into experimental machines during the very slow commercial expansion of magneto generators in the 1860's. These basic modifications were changes in the design of the armature, the substitution of electromagnets for permanent magnets as a means of producing the field, and the introduction of self-excitation where the current induced in the armature passed through the field coils and produced the field in which the armature is placed. The last modification was the one that is considered characteristic of the dynamo. Although it took over a decade for these innovations to be combined in one machine, they laid the foundation for the modern dynamo.

The first basic improvement in the form of the armature was due to Werner Siemens, at that time a well-known telegraph inventor and one of the partners in the Siemens and Halske firm in Berlin. In 1856 he replaced the disk armature that had been used in practically all the previous machines by a much simpler one shaped like a weaver's shuttle, with

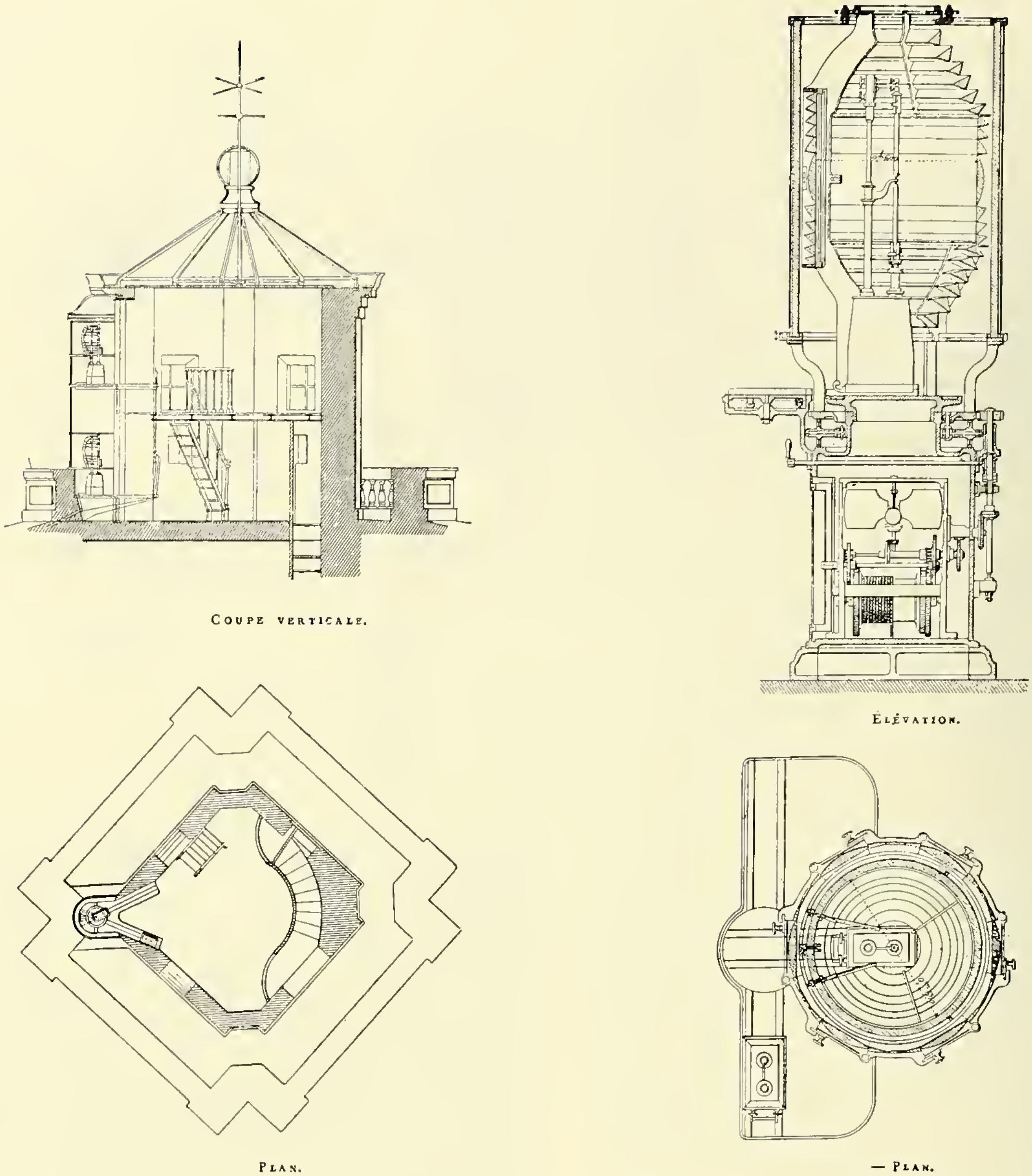


Figure 44.—Details of the arrangement of the arc light in the lighthouse at Cap de la Hève. From E. Allard, *Phares et balises*, vol. 5 of *Les Travaux publics de la France*, L. Reynaud, ed., Paris, 1883, pp. 110, 111.

an H cross-section.[75] The wire was wound longitudinally into the cavities in the armature and the ends of the wire were led out to a commutator divided into two parts. The armature was spun on its long axis between rounded-out cavities in the poles of the field magnets (fig. 49).

This shuttle-type armature was more efficient mechanically than the disk armature. Because of its more compact form, the shuttle armature could be driven with less power than could a disk armature of

[75] British patent 2107 (provisional specification filed September 10, 1856); Werner Siemens, "Ueber eine neue Construction magneto elektrischer Maschine," *Annalen der Physik und Chemie*, 1857, vol. 101, pp. 271–274.

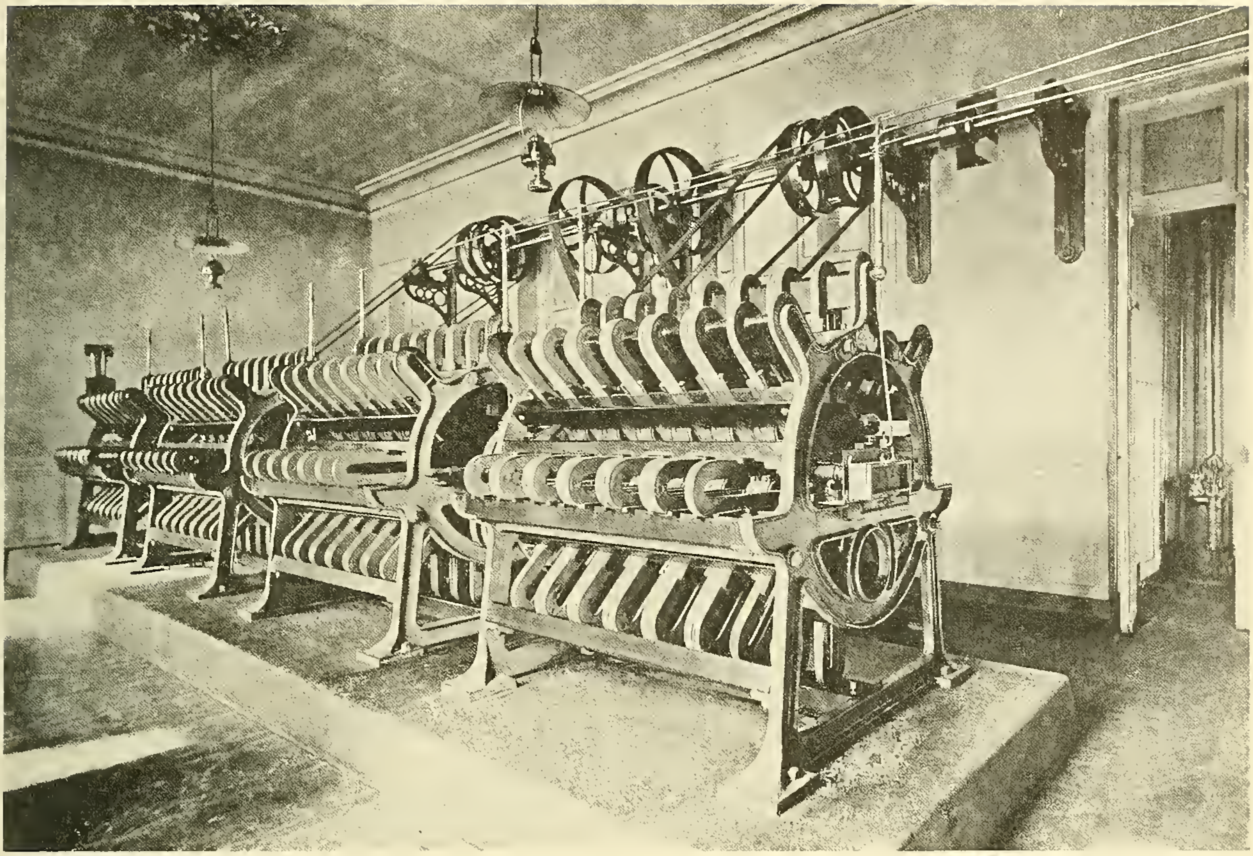


Figure 45.—Generator room in the south lighthouse at Cap de la Hève, showing the two sets of Alliance generators. From E. Allard, *Phares et balises*, vol. 5 of *Les Travaux publics de la France*, L. Reynaud, ed., Paris, 1883, 48th plate at end of volume.

the same weight. Also, the more compact form made possible a more rigid structure, and Siemens could reduce the air gap between the magnetic pole and the armature to a very small amount, thus increasing the magnetic flux cut by the wires of the armature as well as the speed of rotation. Moreover, the armature was located between the poles where the flux density was greatest instead of beside the poles where the flux density was much less. Consequently, the over-all electrical efficiency was increased to the point where the heating of the armature became a problem for the first time. Because of these advantages, the shuttle armature was used in the most successful generators of the next decade or so. Siemens applied his shuttle generator to operate an indicator telegraph.

Another innovation that seemed to promise still greater efficiency was the ring armature, first devised by a man named Elias in the 1840's (fig. 50). Antonio Pacinotti, a student at the University of Pisa, again invented such an armature for an electric motor in 1863 (figs. 51, 52) but his call to military duties prevented him from developing it.[76] The practical development of the ring armature was due to Zénobe T. Gramme who, in 1870, patented a magneto generator with a toroidal core of soft iron wire that had many coils of copper wire wound around the core and

[76] Antonio Pacinotti, "Descrizione di una macchinetta elettromagnetica," *Il Nuovo Cimento*, 1863, vol. 19, pp. 378–384; "Sur une Machine électromagnétique, construite en 1860, d'après le même principe que la machine de M. Gramme," *Comptes rendus*, 1871, vol. 73, pp. 543–544; Franklin L. Pope, "The Genesis of the Modern Dynamo—Antonio Pacinotti," *Electrical Engineer*, 1892, vol. 14, pp. 259–262, 283–284, 307, 339–341.

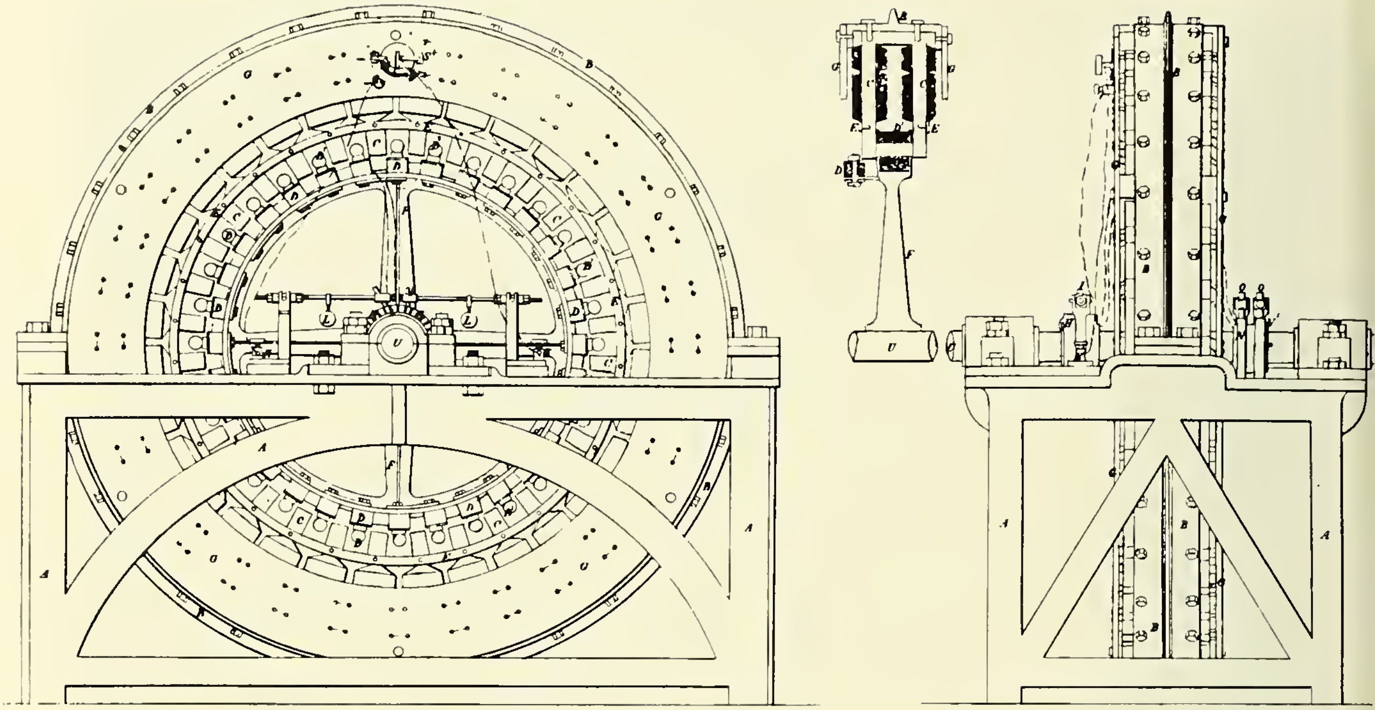


Figure 46.—Patent drawing of Holmes' alternator of 1867. From British patent specification 2307, August 10, 1867.

joined so as to form one continuous closed coil.[77] Connections from the many subdivisions of the coil led to the numerous corresponding commutator bars on the axis of the armature (figs. 53–55).

While the shuttle armature of Siemens was more efficient than the Alliance disk armature, much current was wasted in the open-circuit coil in commutation; that is, in the reversal of the direction of the current at each revolution which led to sparking at the brushes. Gramme's closed circuit coil, with its many-part commutator, mitigated the problem of commutation and produced a steadier output. In addition, Gramme's armature had a considerable advantage over the Siemens armature in that it did not become excessively hot. However, since the wire on the inside of the ring armature was shielded by the wire on the outside, not all the coil was useful in producing the output current and the resistance of the armature was greater than it need be.

The most efficient armature, and the basis of the modern one, is the drum armature, which was worked out in March 1872 by Friedrich von Hefner-Alteneck, chief engineer at the Siemens and Halske factory in Berlin and first exhibited at the Vienna Exposition of 1873 (fig. 56). Von Hefner-Alteneck devised an armature with a method of winding that minimized the unproductive end-turns that did not cut the magnetic field, but his armature still retained the advantage of the Gramme ring in commutation. Instead of winding the wire about a torus, Von Hefner-Alteneck wound the wire about the outside of a drum-shaped armature. If he had threaded the turns through the interior of the cylinder, it would have been topologically the same as winding a torus; instead, he passed the wire directly across the end faces of the cylinder to a point on the opposite lateral wall. This resulted in only the end-turns not cutting the lines of force. The relative amount of unproductive wire was further reduced by making

[77] French patent 87938 (November 22, 1869; additions, April 11, 1870, and February 27, 1872; the first addition concerned the ring armature); British patent 1668 (June 9, 1870).

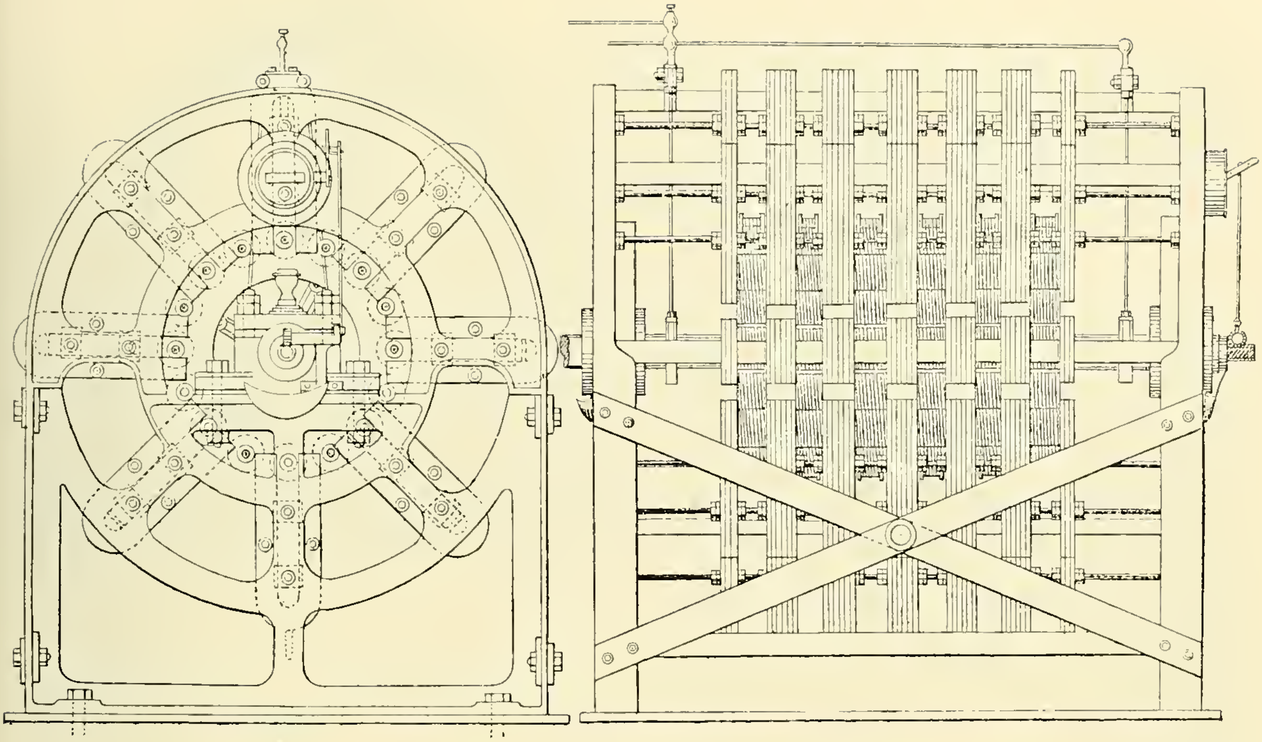


Figure 47.—Holmes' alternator at the Souter Point lighthouse. From *La Lumière électrique*, October 7, 1882, vol. 7, p. 341.

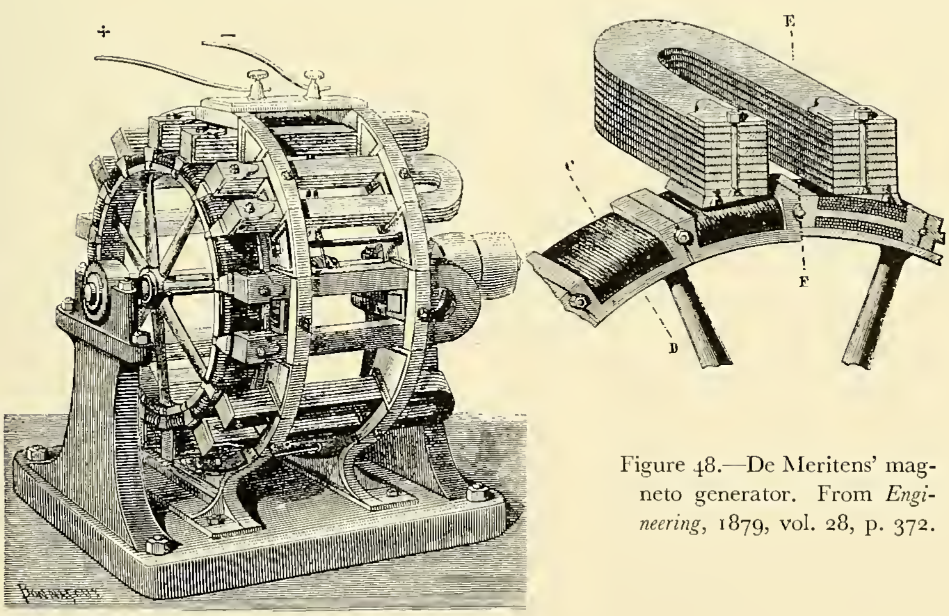


Figure 48.—De Meritens' magneto generator. From *Engineering*, 1879, vol. 28, p. 372.

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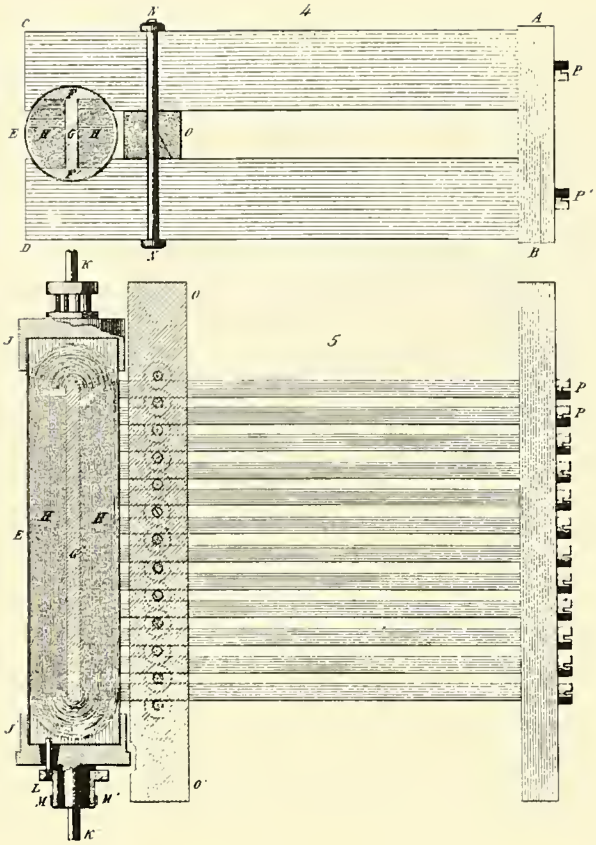


Figure 49.—Siemens' magneto generator, using his shuttle armature. The armature coil (*HH*) was wound upon the armature core (*FGF'*). From E. W. Siemens, "Ueber eine neue Construction magnetoelektrischer Maschinen," *Annalen der Physik*, 1857, vol. 101, fig. 2.

the cylinder long with respect to the diameter. Another modification was that, instead of the single coil of wire as in the Siemens armature, there were now 16 coils that had their terminals reversed twice each revolution. The 2-part commutator of Siemens was accordingly replaced by a 16-part one. The coils were interconnected at the commutator bars so as to form a single closed-circuit coil.[78]

Nevertheless, heating of the armature was a considerable problem in the original design of 1873.

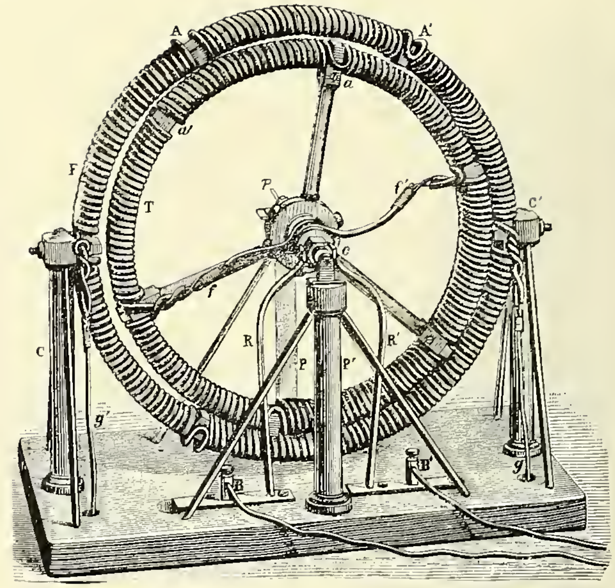


Figure 50.—Ring armature devised by Elias in the 1840's. It was designed for a motor rather than for a generator. From *La Lumière électrique*, 1882, vol. 7, p. 14, fig. 13.

In order to avoid this, Von Hefner-Alteneck fixed the soft iron core of the armature and rotated the coils. Siemens tried to reduce the temperature by water cooling and by laminating the armature, but the former method was too awkward to be practical, and the latter one was unsuccessful at the time.

Very few drum armature dynamos were made and sold; however, the 1876 exhibition in South Kensington showed that these originally unpromising generators had been reduced to practice. The tests of Tyndall and Douglass proved them to be the most efficient of all the units they compared. The armature no longer overheated as it had in the earlier stages of its development, and its output was more constant. In addition, provision was made to reduce sparking at the commutator by including an arrangement for shifting the position of the brushes.

At first the drum armature did not seem as practical as the ring armature, for it was quite difficult to wind the coils on the drum and to insulate the successive coils from one another; so, the advantage of the many-part commutator of Gramme seemed lost. In addition, ventilation was much easier for the ring than for the drum, particularly when the drum was a solid rather than a hollow cylinder.

[78] British patent 2006 (June 5, 1873); French patent 99828 (July 5, 1873; addition, June 21, 1878); *Engineering*, 1873, vol. 16, p. 490; Higgs and Brittle, *op. cit.* (footnote 72); James Dredge, ed., *Electric Illumination*, London, 1882, vol. 1, pp. 275–293.

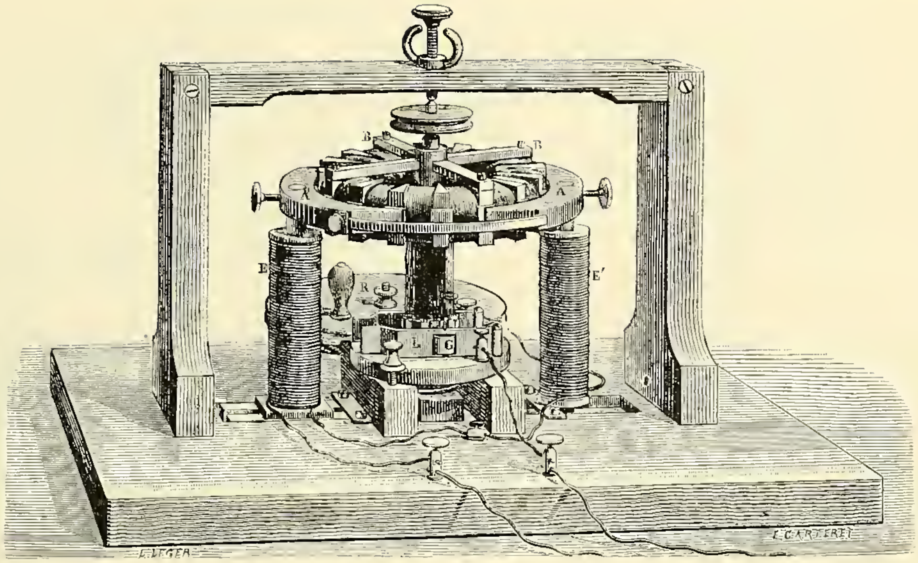


Figure 51.—Pacinotti's ring armature, as used in a motor, with a field produced by electromagnets. Pacinotti found he could use the machine as a generator by replacing the field electromagnets with permanent magnets. From *La Lumière électrique*, 1882, vol. 7, p. 15, fig. 14.

But the inherent advantages of the drum armature were greater. After it was discovered that the coils could be inserted in slits on the core and better methods of laminating the core and of winding the coils were introduced, the drum armature was put to use; it has remained in use to the present time.

But the production of current in all these early generators was hampered considerably by the lack of sufficiently strong fields. Charles Wheatstone had introduced electromagnets into the generator that he used for his telegraph of 1845, but this arrangement was generally deemed too clumsy as it required chemical cells in addition to the generator itself.[79] In 1864, Henry Wilde patented a generator in which a magneto was substituted for the chemical cells (fig. 57). The current from the magneto was then used to excite the electromagnet field coils of another generator. One motor drove both magneto generator and electromagnet generator.[80] A few years later William Ladd simplified the double structure by combining the two separate fields in one unit (fig. 58). Wire was wound around permanent bar magnets which were placed parallel to and above each other. An armature was rotated between each pair of poles at the end of the magnets. One armature provided current for the coils on the permanent magnets and so added to the latter's field while the output current was taken from the other armature.[81]

When demonstrated at the Paris Exhibition of 1867, both Wilde's and Ladd's machines produced

[79] British patent 10665 (May 6, 1845).

[80] British patent 3006 (June 4, 1864); Henry Wilde, "Experimental Researches in Magnetism and Electricity," *Philosophical Magazine*, 1866, ser. 4, vol. 32, pp. 148–152, and 1867, ser. 4, vol. 34, pp. 81–104; *Les Mondes*, 1866, vol. 11, pp. 319–324, 373, 629–636; vol. 12, pp. 24–26; Théodose du Moncel, *Exposé des applications de l'électricité*, Paris, 1872–1878, ed. 3 (5 vols.) vol. 2, pp. 226–230.

[81] William Ladd, "On a Magneto-Electrical Machine," *Philosophical Magazine*, 1867, ser. 4, vol. 33, pp. 544–545; "On a New Form of Dynamo-Magnetic Machine," *Reports of the British Association for the Advancement of Science*, 1867, vol. 37, pp. 13–14; "On a Further Development of the Dynamo Magneto Electric Machine," *Reports of the British Association for the Advancement of Science*, 1868, vol. 38, pp. 19–20; Du Moncel, *op. cit.* (footnote 80), vol. 2, pp. 230–234.

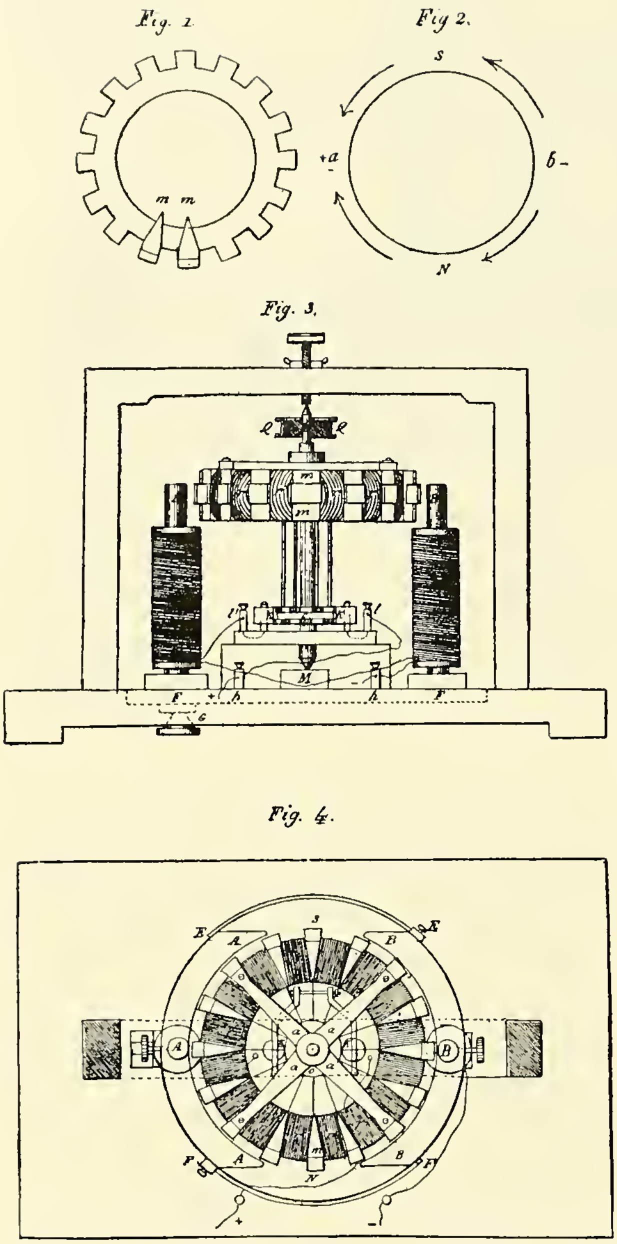


Figure 52.—Pacinotti's illustrations in the original pamphlet describing his machine, as reproduced in *Electrical Engineer*, September 21, 1892, vol. 14, p. 260.

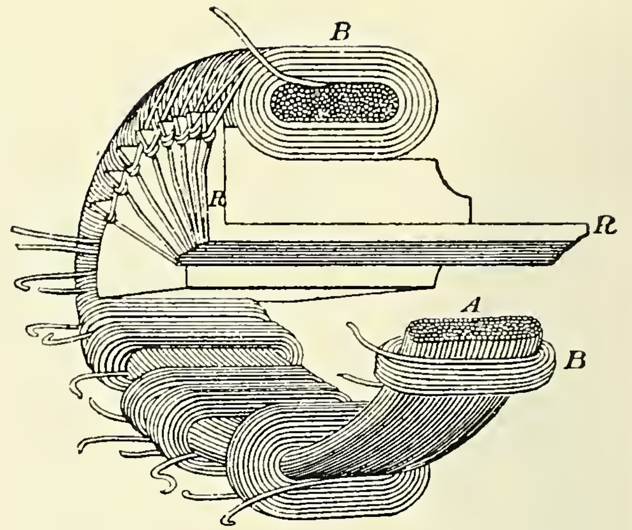


Figure 53.—Gramme's ring armature, showing the many coils (*B*) that were connected to commutator plates (*R*). From S. P. Thompson, *Dynamo-Electric Machinery*, ed. 2, London, 1886, p. 116.

sufficient power to maintain an arc light, to the great astonishment of the spectators. The small size of these generators provided a striking contrast to the bulky magneto generators of the Holmes and the Alliance systems that also were exhibited. The Wilde machines were so promising that within two years the Alliance company had purchased the French patent; the Scottish commission for lighthouses was trying them in an installation; and the Elkington firm in England was using a number of them for electroplating.[82]

However, by that time the next step—that of self-excitation—had been taken, and the machines of 1867 already were potentially outmoded. Some isolated efforts at self-excitation had been made by Søren Hjorth[83] of Denmark in 1851, by Wilhelm Sinsteden[84] of Germany in 1861, and by Moses

[82] *Les Mondes*, 1867, vol. 14, pp. 161–165; 1869, vol. 21, pp. 152–154; 1871, vol. 26, pp. 94–96.

[83] British patent 2198 (provisional specification filed October 14, 1854); Sigurd Smith, *Søren Hjorth, Inventor of the Dynamo-Electric Principle*, Copenhagen, 1912.

[84] Wilhelm Sinsteden, "Ueber die Anwendung eines mit einer Drahtspirale armirten Stahlmagnets in der dynamo-elektrischen Maschine," *Annalen der Physik und Chemie*, 1869, vol. 137, pp. 289–296.

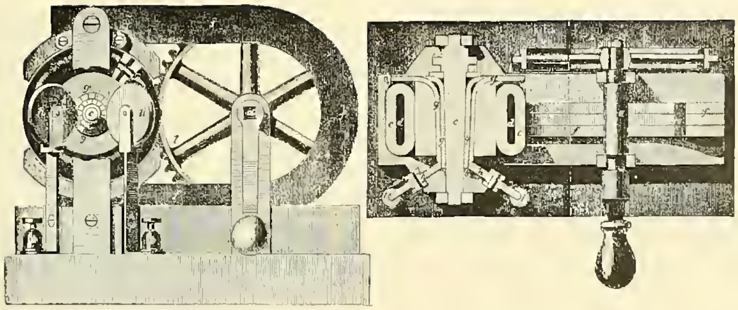


Figure 54.—Gramme's magneto with his ring armature. Note the disk-shaped current collectors. From *Chronique de l'industrie*, April 17, 1872, p. 84.

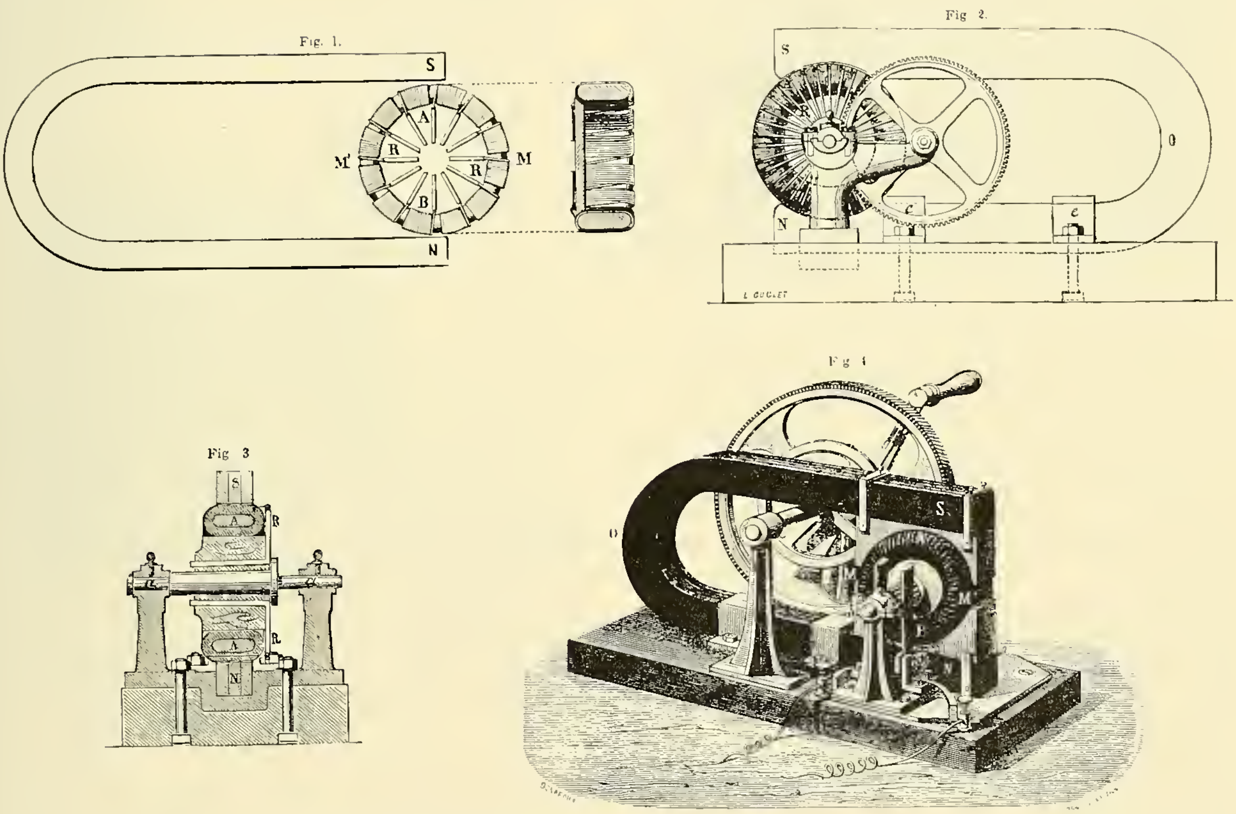


Figure 55.—A slightly later version of Gramme's magneto with ring armature, showing the many-part commutator and the use of wire brushes as current collectors. From *Chronique de l'industrie*, August 13, 1873, p. 223.

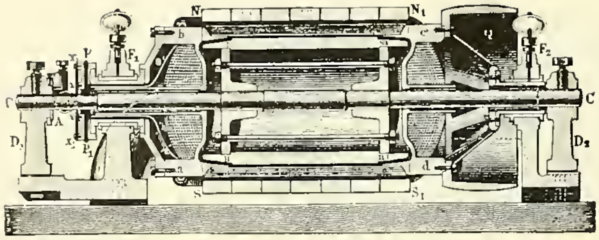
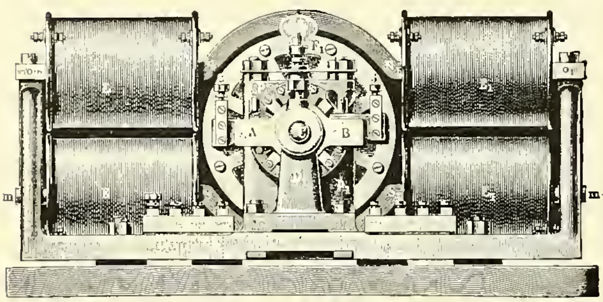


Figure 56.—Two views of the Von Hefner-Alteneck dynamo with drum armature as shown at the Vienna Exhibition of 1873. The armature core (s–s_1, n–n_1) is fixed and the armature windings (coiled on *abcd*) rotate. From J. Dredge, *Electric Illumination*, London, n.d. (about 1882), vol. 1, p. 278.



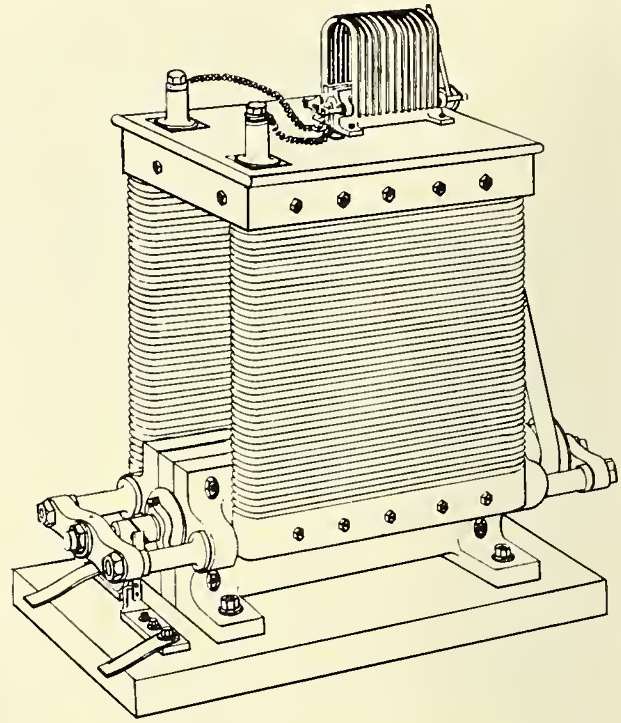


Figure 57.—Wilde's application of a magneto generator to provide the electromagnet field of a second generator. From *Philosophical Magazine*, 1867. vol. 34, pl. 2.

Farmer[85] of the United States in 1865 but their work did not lead to further development. A few years later, in 1867, the principle of self-excitation was simultaneously enunciated by Charles Wheatstone,[86] by S. Alfred Varley,[87] and by Werner Siemens (figs. 59–61).[88] The discoveries of Wheatstone and Siemens were even announced at the same meeting, in London.

The basic theory of self-excitation is simple. All iron is magnetized to some extent, however slight it may be, and it is sufficient to induce some current in the armature of an electromagnet generator when the armature is rotated between the poles of the electromagnet before any current flows through the electromagnet and before the core of the electromagnet is "magnetized." If connections are made so that this current passes through the electromagnet, it will increase the magnetic field in which the armature turns, and this in turn increases the induced current, and so on. Under proper conditions, the process will continue until the core of the field magnet

[85] H. Wilde, "On Siemens' and Wheatstone's Magneto-Electric Machines," *Proceedings of the Literary and Philosophical Society of Manchester*, 1867, vol. 6, pp. 103–107; George B. Prescott, *Dynamo-Electricity*, New York, 1884, p. 123.

[86] *Philosophical Magazine*, 1867, ser. 4, vol. 33, pp. 471–474.

[87] British patent 3394 (December 24, 1866); also, *Engineering*, 1877, vol. 24, pp. 322, 348.

[88] Werner Siemens, "Ueber die Unwandlung von Arbeitskraft in elektrischen Strome ohne Anwendung permanenter Magnete," *Monatsberichte der Koeniglichen Akademie der Wissenschaften zu Berlin*, 1867, pp. 55–58; C. William Siemens, "On the Conversion of Dynamical into Electrical Force without the Aid of Permanent Magnetism," *Philosophical Magazine*, 1867, ser. 4, vol. 33, pp. 469–471; British patent 261 (filed January 31, 1867); Adolf Thomälen, "Zur Geschichte der Dynamomaschine," *Beiträge zur Geschichte der Technik und Industrie*, 1917, vol. 7, pp. 134–168. For an excellent introduction to the early history of the dynamo, see Otto Mahr, *Die Entstehung der Dynamomaschine*, vol. 5 of *Geschichtliche Einzeldarstellungen aus der Elektrotechnik*, Berlin, 1941, pp. 129–140.

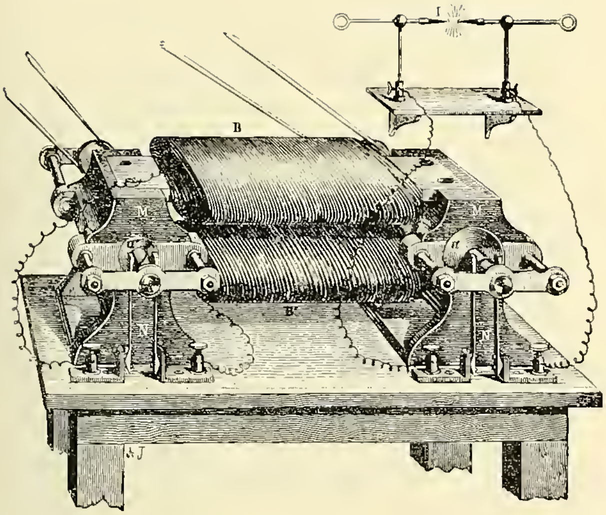


Figure 58.—Ladd's combination magneto-electromagnet generator as used to drive an arc light. From *La Lumière électrique*, 1882, vol. 7, p. 13, fig. 12.

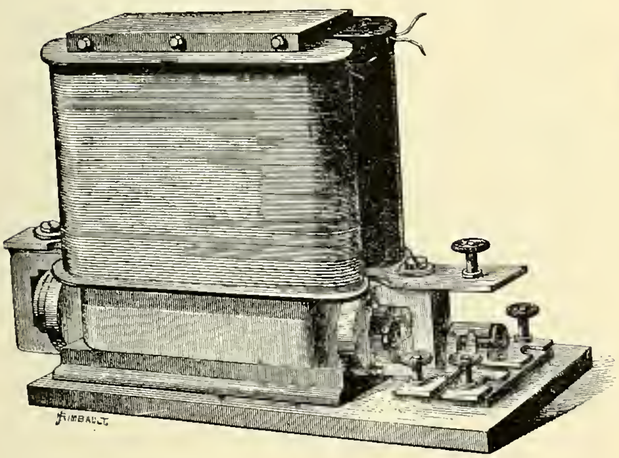


Figure 59.—Wheatstone's dynamo of 1866. From J. Dredge, *Electric Illumination*, London, n.d. (about 1882), vol. 1, p. 137.

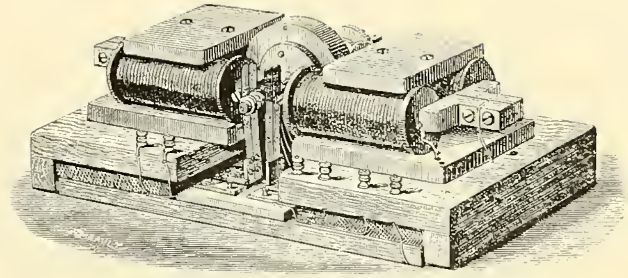


Figure 60.—Varley's dynamo of 1866. From J. Dredge, *Electric Illumination*, London, n.d. (about 1882), vol. 1, p. 138.

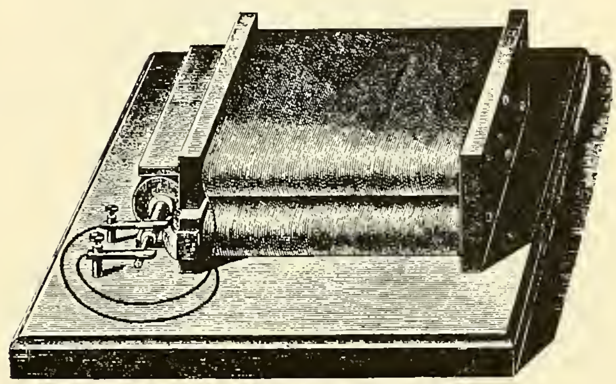


Figure 61.—Siemens' dynamo of 1866. From A. Thomälen, "Zur Geschichte der Dynamo-Maschine," *Beiträge zur Geschichte der Technik und Industrie*, 1916, vol. 7, p. 141.

is magnetically saturated and no further increase in current is possible at that particular speed of armature rotation. The distinctive term "dynamo-electric machine," in contrast to the usual term "magneto-electric machine," was applied to this new kind of generator by Werner Siemens in his announcement of the new principle. Since then, the term has been shortened to "dynamo."

Gramme was the first to make the dynamo a success commercially.[89] He was a Belgian carpenter who worked with a compatriot, Joseph van Malderen, at the shop of the Société l'Alliance as model-maker. As Gramme's interest in electricity grew, he left the shop to further his education and to become an instrument-maker by working with Ruhmkorff and then Disdéri (or, some say, Froment). He finally turned to working out his own ideas, and his first

[89] O. Colson, "Zénobe Gramme: Sa Vie et ses oeuvres," *Wallonia*, 1903, vol. 11, pp. 261–279; Jean Pelseneer, *Zénobe Gramme*, Brussels, 1944, ed. 2.

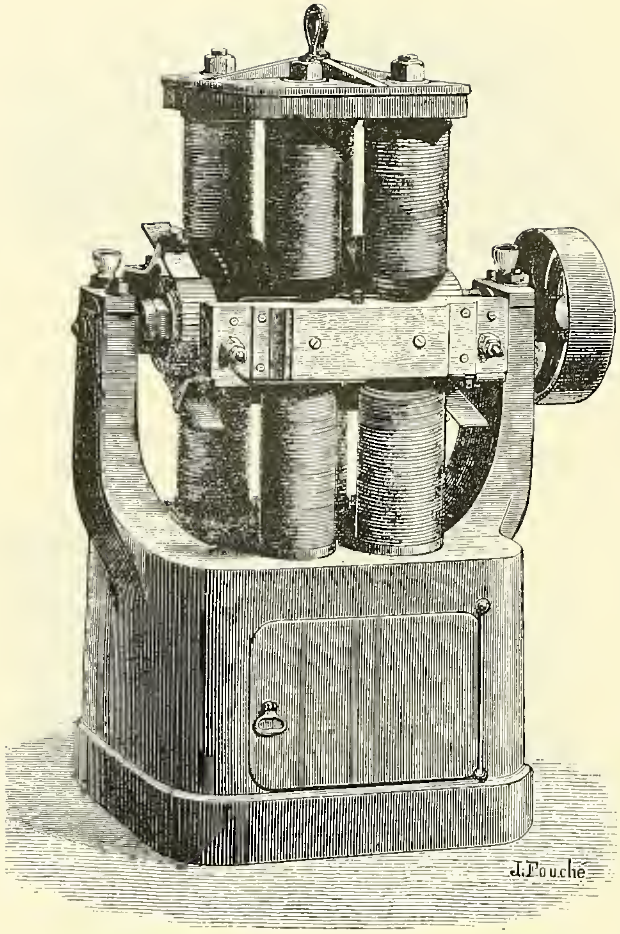


Figure 62.—Gramme's first commercial dynamo for electroplating. From *Revue industrielle,* November 25, 1874, p. 406, fig. 5.

inventions of the 1860's were based on magneto-electric machines of the multiple-disk Woolrich type, although one of the specifications in his patent of February 26, 1867, implied self-excitation.[90] As mentioned previously, he patented the ring armature in 1870.

With the Count d'Ivernois as financial backer, and Hippolyte Fontaine as the director, the Société des Machines Magneto-électriques Gramme was founded sometime during the winter of 1870–1871 to manufacture a generator with the new type of ring armature; however, the Franco-Prussian war and its consequences delayed the entrepreneurs for a time. Instead the Société commissioned the instrument-maker Bréguet to make magneto generators with a ring armature in the early 1870's for laboratory and small shop use.[91] The experience gained by varying the form of these small magneto generators served as a guide in the later construction of the Gramme dynamo.

In 1871 Gramme presented to the Académie des Sciences a generator based on Ladd's design but with Gramme's ring armatures instead of Siemens' shuttle armatures. A parallel pair of horizontal bar-electromagnets, one above the other, had ring armatures between the poles at each end of the pair. One ring armature supplied current for the electromagnets and the other supplied the output current. An article appearing in the *Comptes rendus* brought the new kind of armature to the attention of the scientific world and served to stimulate several investigators to try to determine how the current was induced in it.[92]

Gramme patented in 1872 a machine that combined the use of the ring armature, wire brushes to collect the current from the armature, and field excitation by a magneto, the armature of which was on the same arbor as that of the electromagnet generator. By the end of that year the first commercial Gramme generator appeared on the market (figs. 62, 63).[93] While this machine was still based on the design of Ladd's apparatus, the modifications considerably improved the efficiency. Instead of using bar-electromagnets arranged horizontally, Gramme used cylindrical electromagnets and arranged them verti-

[90] French patent 75172 (February 26, 1868; additions, November 21, 1868, and August 13, 1869).

[91] *Chronique de l'industrie,* 1872, vol. 1, pp. 84, 179–180; Du Moncel, *op. cit.* (footnote 80), vol. 2, pp. 219–222; Alfred N. Bréguet, "Gramme's Electro-Magnetic Machine," *Engineering,* 1872, vol. 13, p. 289.

[92] Z. T. Gramme, "Sur une Machine magnéto-électrique produisant des courants continus," *Comptes rendus,* 1871, vol. 73, pp. 175–178; Théodose du Moncel, *op. cit.* (footnote 80), vol. 2, pp. 538–544; "Note sur les courants induits résultant de l'action des aimants sur les bobines d'induction normalement à leur axe," *Comptes rendus,* 1872, vol. 74, pp. 1335–1339; J. M. Gaugain, "Sur les Courants d'induction developpés dans la machine de M. Gramme," *Comptes rendus,* 1872, vol. 75, pp. 138–141, 627–630, 828–831; *Engineering,* 1871, vol. 12, pp. 87, 173.

[93] French patent 87938 (addition of February 27, 1872); Z. T. Gramme, "Sur les Machines magnéto-électriques Gramme, appliquées à la galvanoplastie et à la production de la lumière," *Comptes rendus,* 1872, vol. 75, pp. 1497–1500; *Chronique de l'industrie,* 1873, vol. 2, pp. 86–87, 99, 223–224.

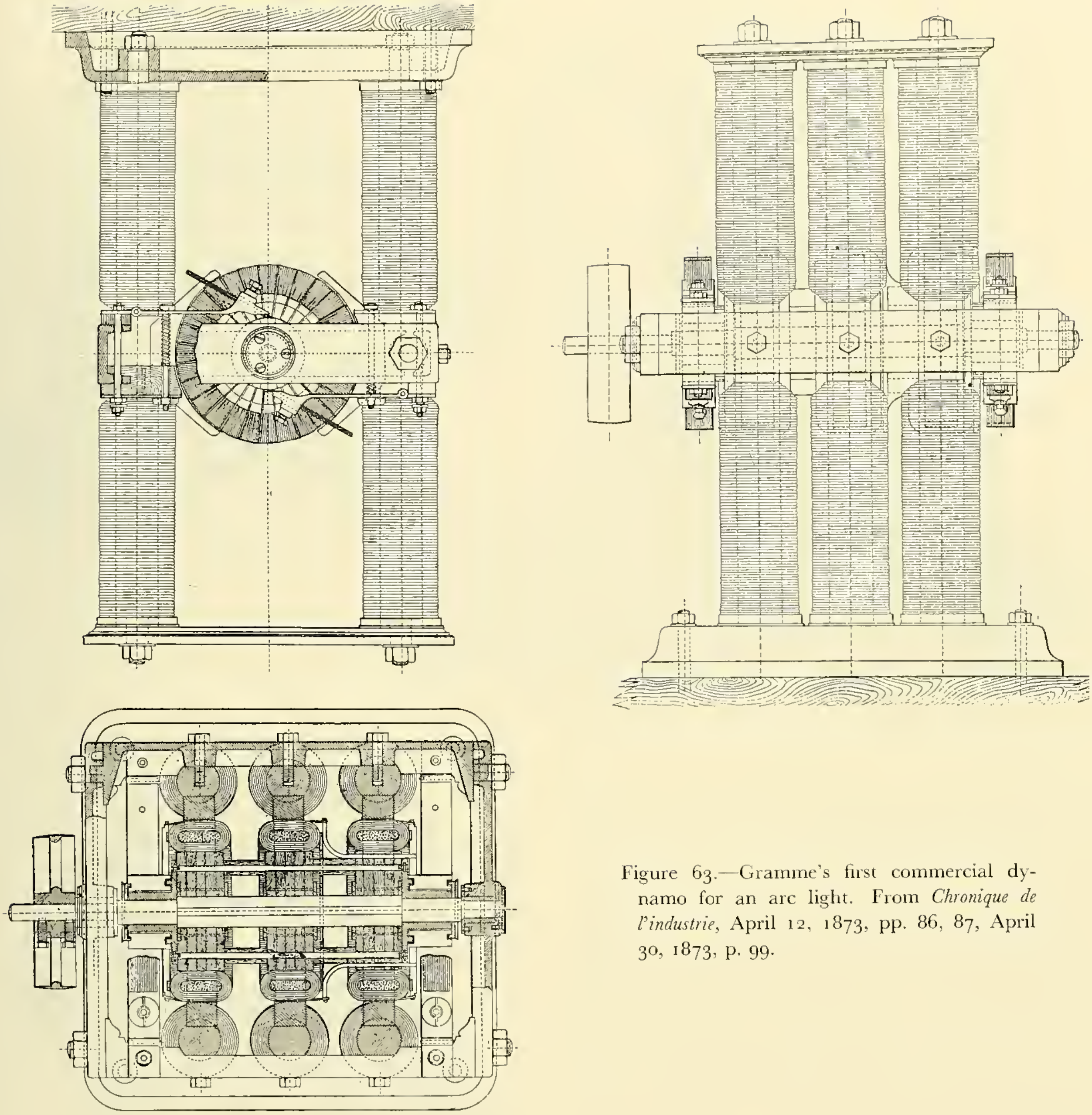


Figure 63.—Gramme's first commercial dynamo for an arc light. From *Chronique de l'industrie*, April 12, 1873, pp. 86, 87, April 30, 1873, p. 99.

cally, and instead of leaving the magnetic circuit open at the ends, he completed the circuit by placing cast-iron plates across the top and bottom of the electromagnets. He provided for the gap in the magnetic circuit in which the armature rotated by leaving a space in the middle of each of the cores of the electromagnets where there were no turns of the field coils. Crescent-shaped pole-pieces were attached to this bare area so as to shunt the magnetic field from one electromagnet to the other and thereby pass through the armatures. The armatures were mounted on a common axis perpendicular to that of the electromagnets and they rotated between the concave faces of the pole-pieces. One of the armatures produced the current for the electromagnets of the other armatures, and brushes of silver-plated copper wire collected the current induced in them.

The generators were made in two forms, one of low

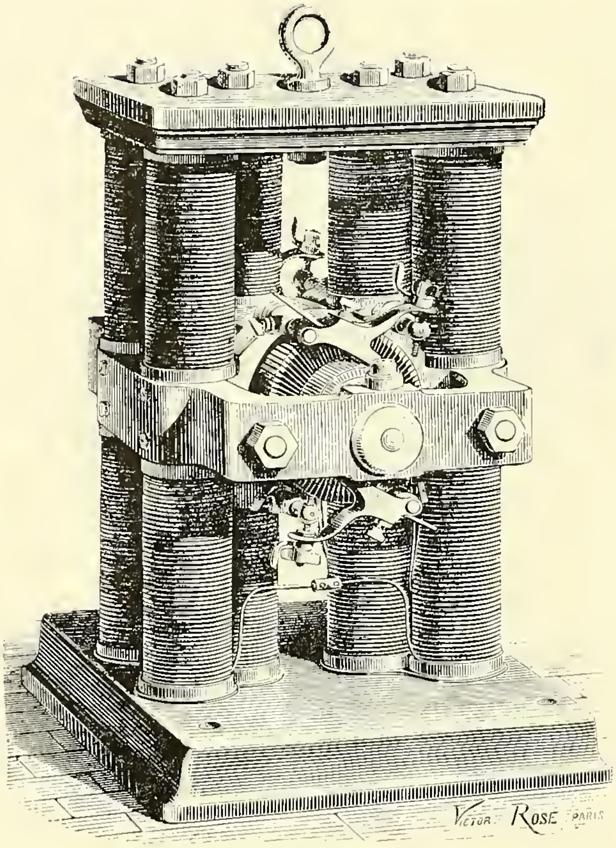


Figure 64.—Gramme's arc-light dynamo, 1874 version. From *Revue industrielle*, November 25, 1874, p. 408.

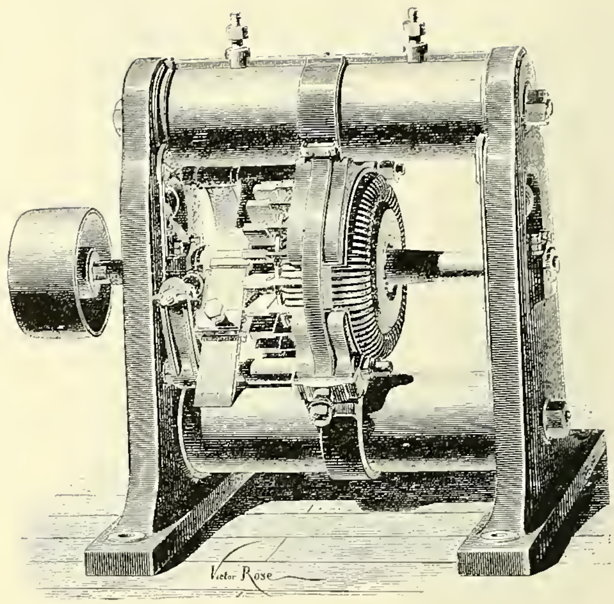


Figure 65.—Gramme's first form of the *type d'atelier* dynamo for electroplating. From *Revue industrielle*, November 25, 1874, p. 407.

resistance with coarse wire on the armature for electrochemical purposes, and one of high resistance with fine wire on the armature for use with arc lights. The high-current electrochemical machine had two armatures on a common axis and four electromagnets. It weighed about 750 kg., measured 0.8 meters square by 1.3 meters high, and required 175 kg. of copper wire. When driven by a 1-hp. engine at 300 r.p.m. it produced about 150 amperes at 2 volts, which implied an efficiency of about 40 percent. The high-voltage arc-light machine used three armatures and six electromagnets. It weighed about 1,000 kg. and measured 0.8 meters square and 1.25 meters high. The electromagnets required 250 kg. of copper wire and the armature required 75 kg. of copper wire. When driven by a 4-hp. engine at 300 r.p.m. the machine produced a light of about 850 Carcel units, about four times as much as the

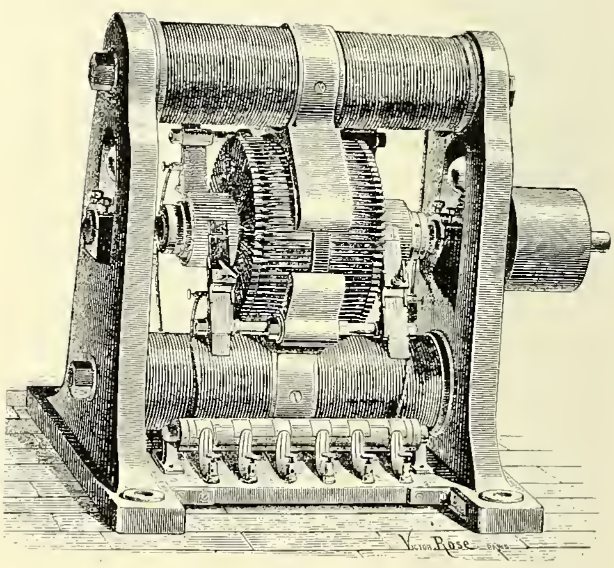


Figure 66.—Gramme's first form of the *type d'atelier* dynamo for arc lights. From *Revue industrielle*, November 25, 1874, p. 409.

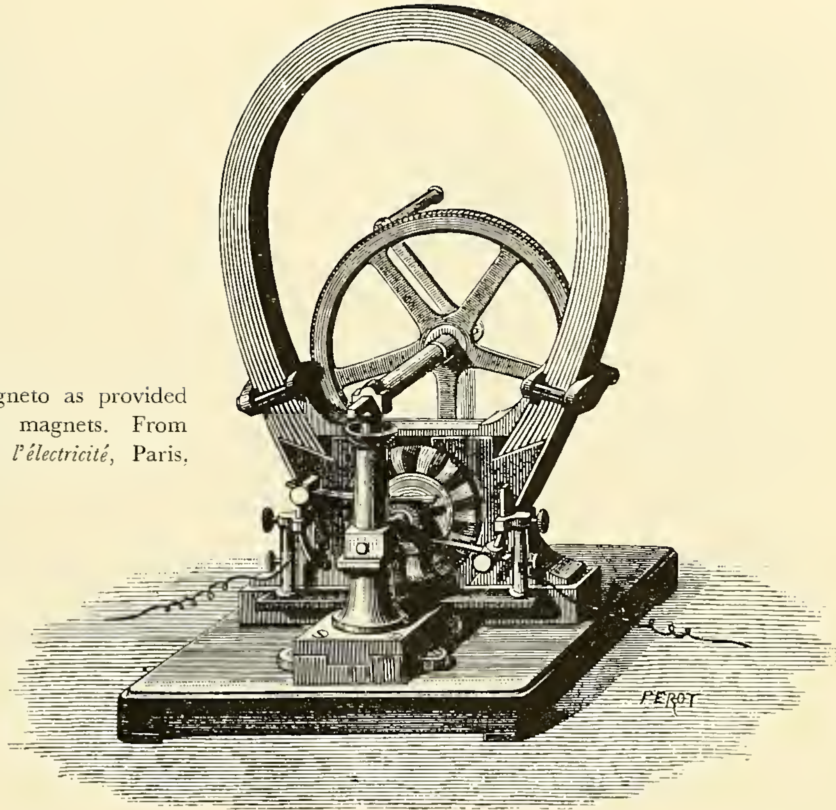


Figure 67.—Gramme's magneto as provided with Jamin's compound magnets. From H. Fontaine, *Eclairage à l'électricité*, Paris, 1877, p. 104.

6-disk Alliance machine. The voltage was equal to that of 105 normal Bunsen cells, and the current was equal to that of 5 such cells. Roughly speaking, such power implied an efficiency of 50 percent. The cost of the machine was £400 in England. Arc-light demonstrations were made in the new Clock Tower of Parliament in London in 1873, but since the machine was quite apt to overheat the arc lights were discontinued in favor of gas.[94]

At the beginning of 1874, Gramme cut down the size and considerably increased the efficiency of both the high-resistance and low-resistance generators by relying completely on the principle of self-excitation.[95] The new model, called the *type d'atelier* (figs. 65, 66), reduced the number of armatures to one and reduced the number of electromagnets necessary to supply the field. The electromagnets were still cylindrical in form but were placed horizontally, with one above the other, as in the original Ladd generator. The axis of the single armature was horizontal and in the same vertical plane as the electromagnets instead of being perpendicular as in the Ladd machine. As before, the magnetic circuit was completed by cast-iron plates at the ends. Other changes made it possible to increase the speed of rotation without excessive heating of the armature.

One electrochemical model and two arc-light models were now produced. The electrochemical machine (fig. 65) weighed 177.5 kg., measured 0.55 meters square by 0.60 meters high, and used only 47 kg. of copper wire for both armature and field. When driven by a ⅔-hp. motor at 500 r.p.m. it would produce the same amount of current as its predecessor. Two sizes of the arc-light machine were made—a large one based on the previous vertical arrangement of the electromagnets (fig. 64) and a small one based on the new horizontal arrangement of the *type d'atelier* (fig. 66). The large arc-light machine used six electro-

[94] *Engineering*, 1873, vol. 15, pp. 291–292.

[95] Z. T. Gramme, "Sur les Nouveaux Perfectionnements apportés aux machines magnéto-électriques," *Comptes rendus*, 1874, vol. 79, pp. 1178–1182; Alfred N. Bréguet, "Machine magnéto-électrique de M. Gramme," *Revue industrielle*, 1874, vol. 3, pp. 405–410; *Engineering*, 1874, vol. 18, pp. 412–414.

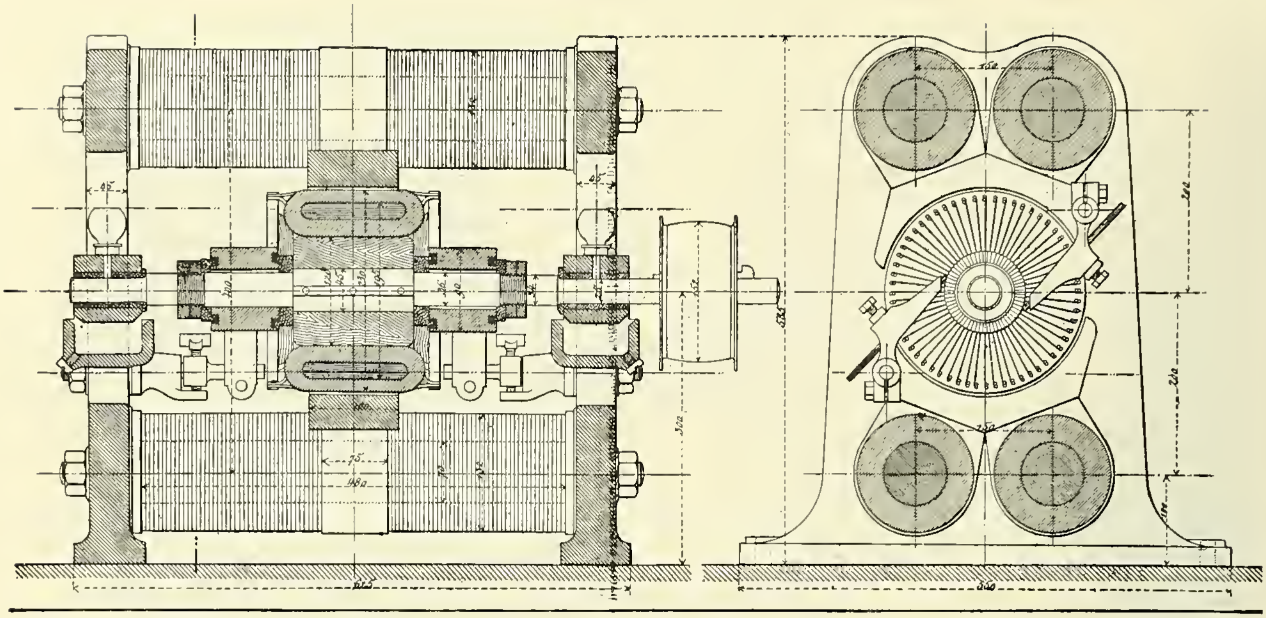


Figure 68.—Gramme's 1876 *type d'atelier* dynamo for use with arc lights. From *Revue industrielle,* February 9, 1876, p. 57.

magnets grouped in the form of a triangle on each side of the armature, and each group had a common pole-piece. This machine weighed 700 kg. and measured 0.90 meter square by 0.65 meter high. There were 180 kg. of copper wire on the electromagnets and 40 kg. on the armature. This large generator normally produced a light of 500 Carcel units, but it was claimed that this amount of light could be almost doubled by increasing the speed of the generator. The smaller machine weighed 183 kg. and measured 0.55 meter square by 0.60 meter high. There were 47 kg. of wire on both armature and field. The armature on the small arc-light machine was what Gramme termed *dédoublé*, that is, there were two windings on the single core with a set of commutator bars on each side of the form (fig. 66).[96] These two windings could then be connected so as to double the current or to double the voltage. The intensity of the arc light at 900 r.p.m. was 200 Carcel units. Small lecture magnetos using Jamin's compound magnets also were produced at this time (fig. 67).

Later improvements enabled Gramme to reduce the cost and increase the efficiency of his generators still

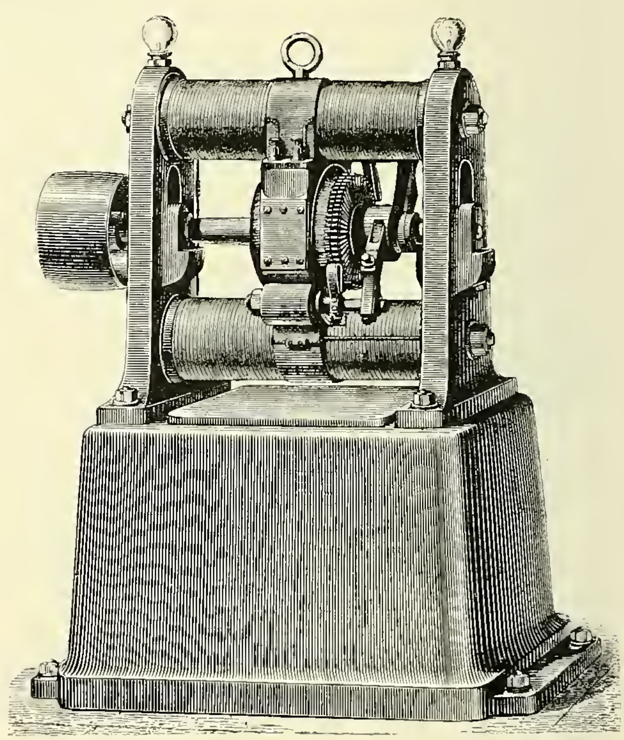


Figure 69.—Gramme's 1877 *type d'atelier* dynamo for use with arc lights. From *Revue industrielle,* May 2, 1877, p. 173.

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96 Alfred N. Bréguet, "Note sur la machine Gramme à l'anneau dédoublé," *Revue industrielle,* 1876, vol. 5, pp. 106–110.

further. In 1876 a smaller and lighter version of the *type d'atelier* generator appeared that weighed 180 kg. and measured 0.60 meter high, 0.35 meter wide, and 0.65 meter long (fig. 68).[97] There were 28 kg. of copper wire on the electromagnets and 4.5 kg. on the armature. When driven by a 2-hp. motor at 820 r.p.m. the generator would produce 200 Carcel units; when driven by a 3-hp. motor at 920 r.p.m. it would produce 400 Carcel units. Another model was brought out in 1877 (figs. 69, 70).

Table 2 gives the values claimed by the French manufacturer for three of the *type d'atelier* models in January 1879 (fig. 71).[98]

Both C and D models had *dédoublé* armatures, so that the two halves of the generator could be connected in quantity (parallel) or in tension (series). In the tabulation, C(T) refers to model C connected in tension, D(Q) to model D connected in quantity, and A(2) to two model A generators. For some reason, the manufacturer gave the light intensity for model A in candles and for models C and D in Carcel units.

By his later improvements Gramme had converted the electric generator from a laboratory curiosity or an awkward magnetoelectric machine into a fully practical dynamo, ready for commercial exploitation. In 1874, four Gramme generators were sold; by 1875, 12 had been sold; by 1876, 85; by 1877, 350; by the middle of 1878, 500; and by 1879, over 1,000. Mechanically, the Gramme dynamo was efficient, compact, and durable; electrically, unlike previous dynamos, it produced a relatively constant output that was greater than that of any previous one, except possibly the Siemens machine. Although the efficiency seems to have ranged between 80 and 90 percent and the main application, until the end of the 1870's, was in the electrochemical industries, the electric light and even the transmission of power was now a possibility.[99]

TABLE 2.—*Manufacturer's claims for three* type d'atelier *models in January 1879.*

Model	*Price* (£)	*Length-width-height* (*inches*)	*Weight* (*lbs.*)	*R.p.m.*	*Hp.*	*Light*	*CP/HP*
A	80	27½ x 15¾ x 22¾	407	900	2. 5	6300	2400
A(2)	160	39 x 19½ x 15¾	748	900	5. 0	14000	2800
C(Q)	240	29 x 21½ x 25½	858	1250	8. 0	2500	310
C(T)	211	29 x 21½ x 25½	858	700	5. 0	1500	300
D(Q)	360	37½ x 31½ x 33½	2200	550	12. 0	4000	300
D(T)	360	37½ x 31½ x 33½	2200	300	7. 0	2000	290

A short time after the commercial appearance of these new dynamos, the world of inventors discovered that such generators could be used as electric motors. This was not a new principle; it had been latent, if not explicit, in all the previous work on generators and motors. Gramme had even noted this in his 1870 patent. However, it was a relatively new theory that a dynamo could be so used, and it was soon found that a better motor than ever before could be produced. The usual story is that the discovery was an accidental one—one of the workers at the Vienna Exhibition of 1873 happened to connect two Gramme dynamos together and found that one generator could drive the other as an electric motor. Hippolyte Fontaine promptly made such an arrangement part of the Gramme exhibit. A centrifugal pump was driven by a Gramme motor that received its power from a Gramme dynamo three-quarters of a mile away; the pump, in turn, supplied a small waterfall (fig. 73). Fontaine was prompt in publicizing his finding that 1 hp. could be transmitted over wires in this manner with an efficiency of about 50 percent. At the Philadelphia Centennial Exposition of 1876, Gramme dynamos were shown running arc lamps, electroplating, and driving another Gramme dynamo as a motor; and by 1879 Fontaine could assert for this process an over-all efficiency of about 63 percent

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[97] Z. T. Gramme, "Recherche sur l'emploi des machines magnéto-électriques à courants continus," *Comptes rendus*, 1877, vol. 84, pp. 1386–1389; Hippolyte Fontaine, "Eclairage à l'électricité," *Revue industrielle*, 1877, vol. 6, pp. 173–174; 1878, vol. 7, pp. 248–250; *op. cit.* (footnote 12), *passim; Engineering*, 1879, vol. 28, p. 64.

[98] Douglass, *op. cit.* (footnote 36), p. 129.

[99] Fontaine, *op. cit.* (footnote 12), p. 89; *Engineering*, 1878, vol. 25, p. 526; M. Mascart, "Sur les Machines magnéto-électriques," *Journal de physique*, 1877, vol. 6, pp. 203–212, 297–305; 1878, vol. 7, pp. 79–92, 363–377; Felix Auerbach and O. E. Meyer, "Ueber die Ströme der Gramme'schen Maschine," *Annalen der Physik und Chemie*, 1879, vol. 8, pp. 494–514; 1880, vol. 9, pp. 676–679; E. Hospitalier, "Sur le Rendement électrique des machines gramme," *La Lumière électrique*, 1879, vol. 1, pp. 114–117.

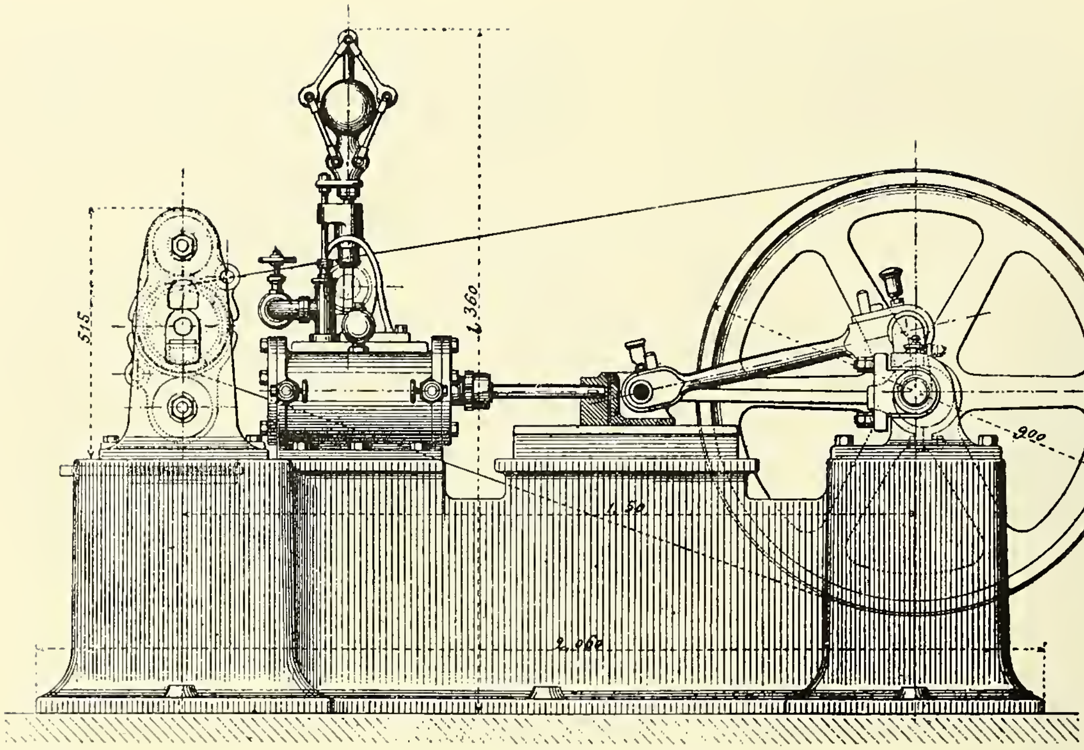


Figure 70.—Gramme's 1877 *type d'atelier* dynamo as driven by a steam engine. From *Revue industrielle*, May 9, 1877, p. 182.

instead of 50 percent (fig. 72).[100] With such examples, a new phase in electrical technology seemed to be opening.

The introduction of the Gramme dynamo into commerce and industry had repercussions in both Europe and America. As mentioned earlier, the firm of Siemens and Halske had exhibited the drum armature in a magneto detonator for mines and in an alternator excited by a separate magneto generator at the Vienna Exhibition of 1873 (fig. 74). A few units with a drum armature were made in the next few years for commercial use, but these, while comparing very favorably with the Gramme dynamo, did not really enter commerce until 1877, after the reports of Tyndall and Douglass[101] were published. In the following two years the English Siemens firm sold more than £60,000 worth of these units.[102] It was probably because of this increasing competition that Gramme countered with his new *type d'atelier* model.

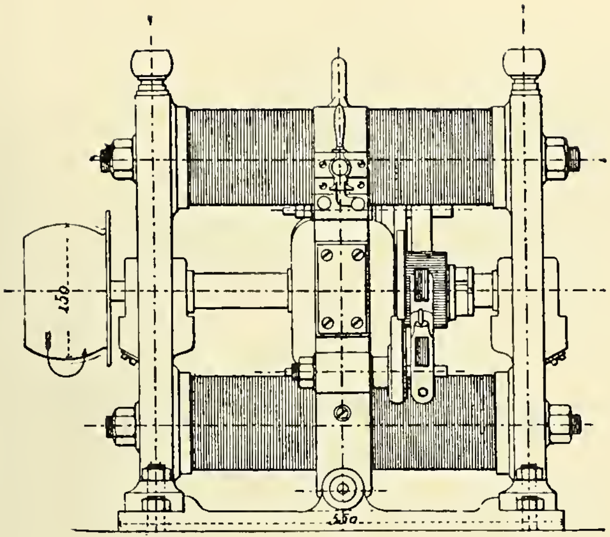
The commercial Siemens machine of the late 1870's (figs. 75–77) had about the same external appearance as the machine displayed at the Vienna Exposition.[103] As with Gramme's early dynamos, it was based on the Ladd machine. A pair of flat bar-electromagnets was placed horizontally, and the axis of the armature was perpendicular to the plane of the electromagnets instead of lying in it, as in Gramme's *type d'atelier*. Since the electromagnets were placed close together,

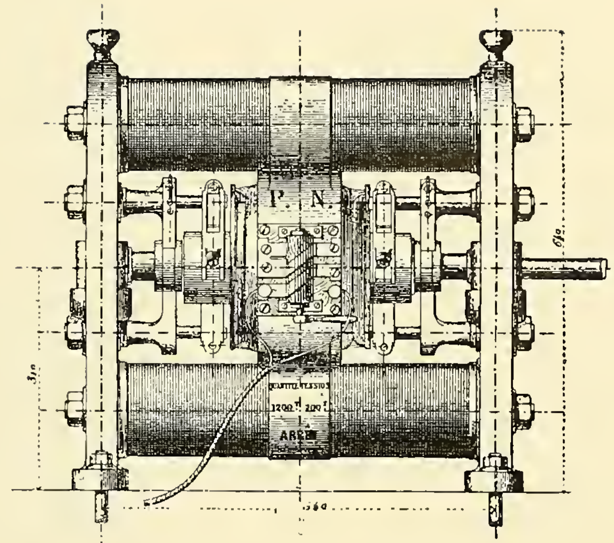
[100] Fontaine, *op. cit.* (footnote 12), pp. 89, 109; *op. cit.* (footnote 19), pp. 127–128; Alfred N. Bréguet, "Notes of Experiments on the Electric Currents Produced by the Gramme Magneto-Electric Machine," *Reports of the British Association for the Advancement of Science*, 1874, vol. 44, pp. 33–34; *L'Illustration*, 1933, vol. 186, p. 411; *Engineering*, 1879, vol. 28, pp. 416–418.

[101] Tyndall, *op. cit.* (footnote 72); Douglas, *op. cit.* (footnote 72).

[102] *Engineering*, 1879, vol. 28, p. 102.

[103] British patent 2006 (June 5, 1873); Du Moncel, *op. cit.* (footnote 80), vol. 5, pp. 525–532; Higgs and Brittle, *op. cit.* (footnote 72); Fontaine, op. cit. (footnote 19); Dredge, *op. cit.* (footnote 78), pp. 275–287.





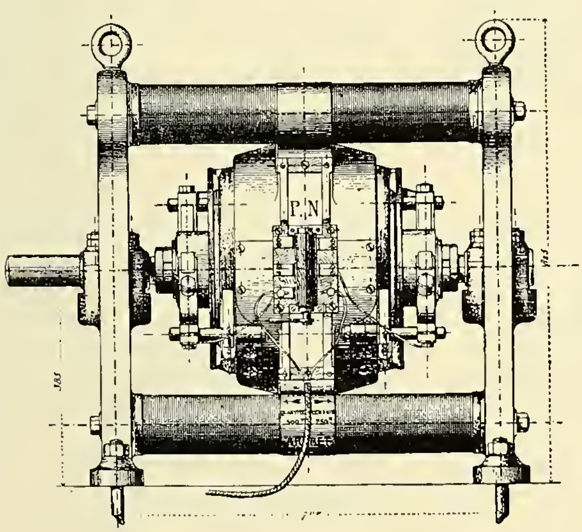


Figure 71.—Gramme's Model A (*top left*), Model C (*above*), and Model D generators of 1879. From *Minutes of Proceedings of Institution of Civil Engineers*, 1879, vol. 57, pp. 126, 127.

the midsection of the cores was pushed aside to form a circular arch to permit the armature to be placed between them. The magnetic circuit was completed by vertical iron plates at the ends. One of the first exact measurements on the efficiency of a dynamo was made by John Hopkinson when he determined the efficiency of the Siemens generator and found it to range between 88 and 90 percent, depending on the amount of current drawn.[104] The Siemens firm also constructed motors (fig. 77d, e).

Higgs and Brittle, two of the men associated with William Siemens in the construction of the English Siemens dynamo, obtained the results [105] shown in table 3 on the three models that the English firm produced.

J. N. Shoolbred made a comparison of the three models of the Siemens machine and the three models of the Gramme *type d'atelier* in 1878.[106] See table 4. As can be readily seen, the Gramme dynamo proved to be superior in each of the three sizes compared. Since all models presumably were tested under the same conditions, and presumably without any bias, these values should be more objective than the others cited.

Another evaluation of the two kinds of machines

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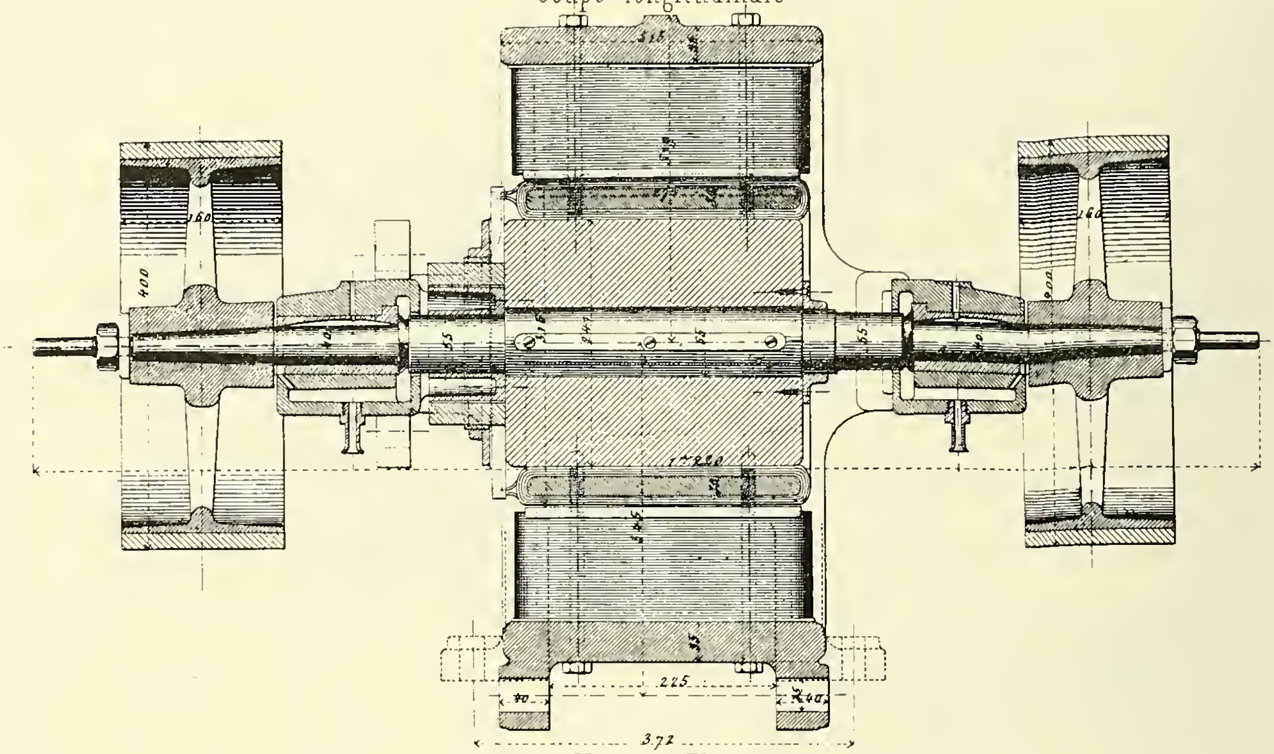
[104] John Hopkinson, "On Electric Lighting," *Proceedings of the Institution of Mechanical Engineers*, 1879, pp. 238–249.

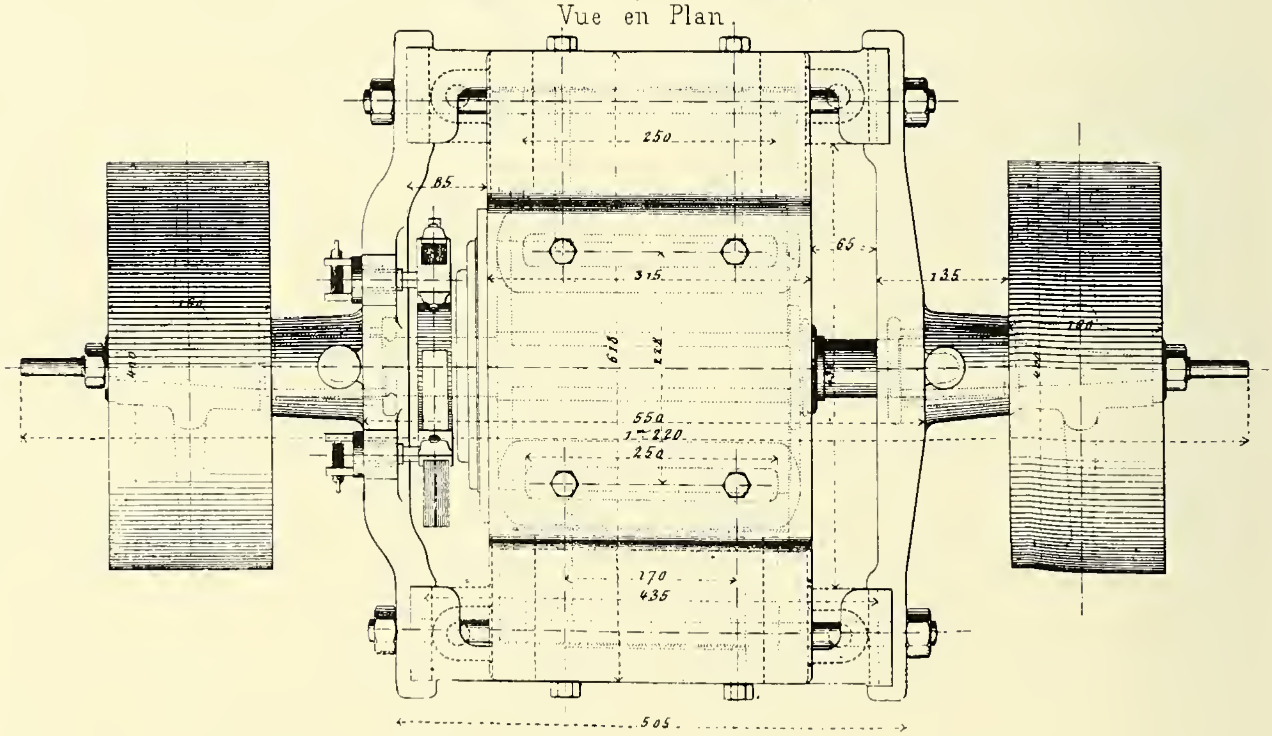
[105] Higgs and Brittle, *op. cit.* (footnote 72).

[106] J. N. Shoolbred, "On the Present State of Electric Lighting," *Engineering*, 1878, vol. 26, pp. 362–365.

Coupe longitudinale



Vue en Plan



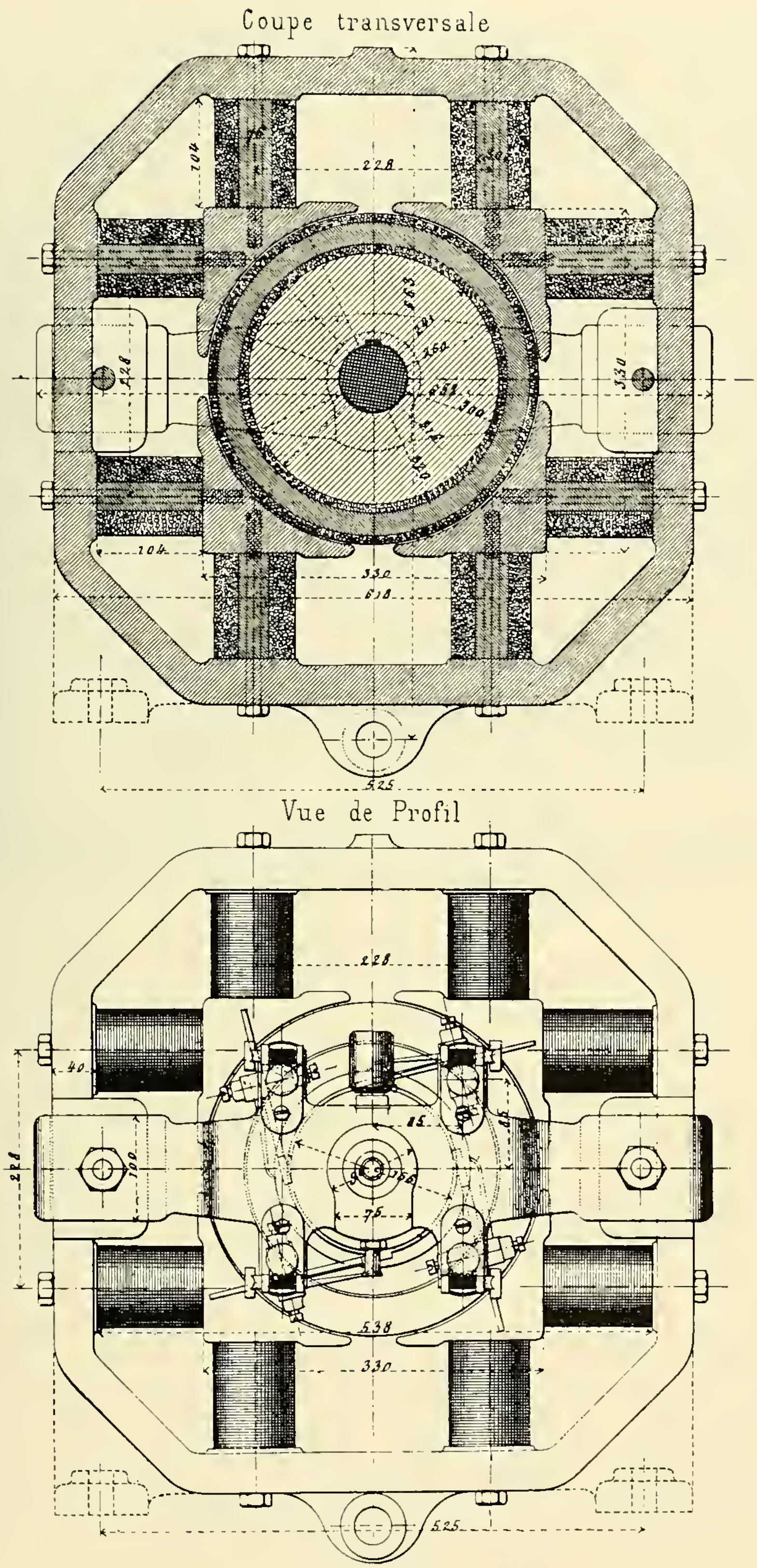


FIGURE 72.—Further steps in the transmission of power: Gramme motors of 1879. From *Revue industrielle*, November 19, 1879, pl. 23.

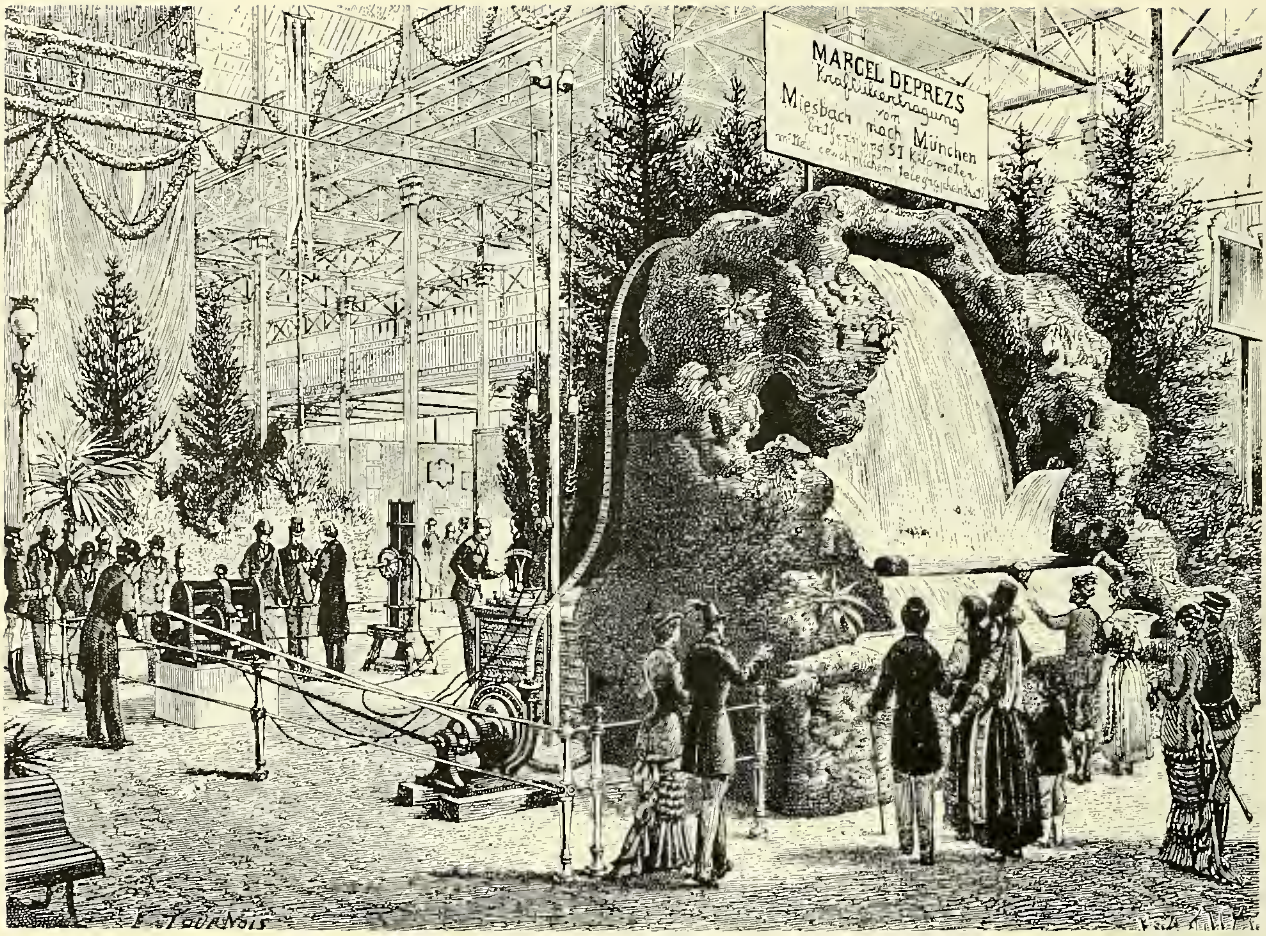


Figure 73.—Marcel Deprez repeats Fontaine's demonstration showing that electric power could be transmitted at a distance. Deprez transmitted his power 57 kilometers to drive a Gramme motor belted to a centrifugal pump at the Munich Exposition of 1882. From *La Lumière électrique*, 1883, vol. 8, p. 131.

was made the following year at the school of military engineering in Chatham, England.[107] See table 5.

[107] "Bericht über Versuche mit elektrischen Lichtapparaten seitens der Militair-Ingenieurschule in Chatham in den Jahren 1879–1880," *Elektrotechnische Zeitschrift*, 1881, vol. 2, pp. 67–71, 105–110.

The two Siemens model B machines were connected in parallel, as were the two Gramme model A generators. While the results are not directly comparable with those of Shoolbred, nevertheless they again suggest the electrical superiority of the Gramme dynamo. On the other hand, the reported efficiency

TABLE 3.—*Data on three models of an English Siemens dynamo produced by Higgs and Brittle.*

Model	*Length-width-height (inches)*	*Weight (lbs.)*	*R.p.m.*	*Light (candles)*	*Hp.*	*CP/HP*
A	25 x 21 x 8.8	298	1100	1000	1. 5–2. 0	500–670
B	29 x 26 x 9.5	419	850	4000	3. 0–3. 5	1150–1330
C	44 x 28.3 x 12.6	1279	480	14800	9–10	1480–1650

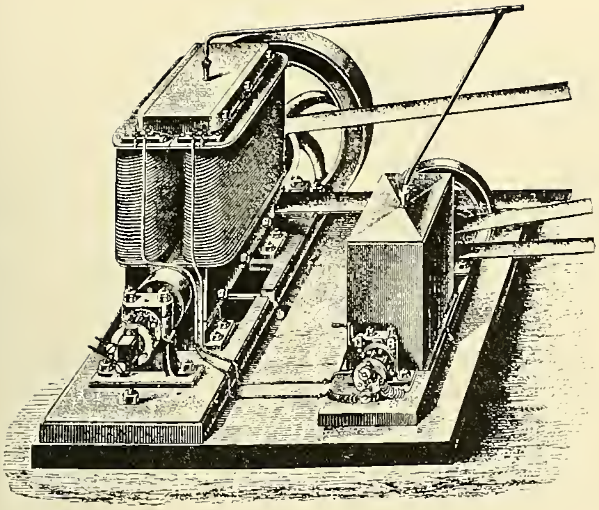


Figure 74.—The Siemens and Halske alternator with external exciter, as shown in Vienna Exhibition of 1873. From A. Thomälen, "Zur Geschichte der Dynamomaschine," *Beiträge zur Geschichte der Technik und Industrie*, 1916, vol. 7, p. 149.

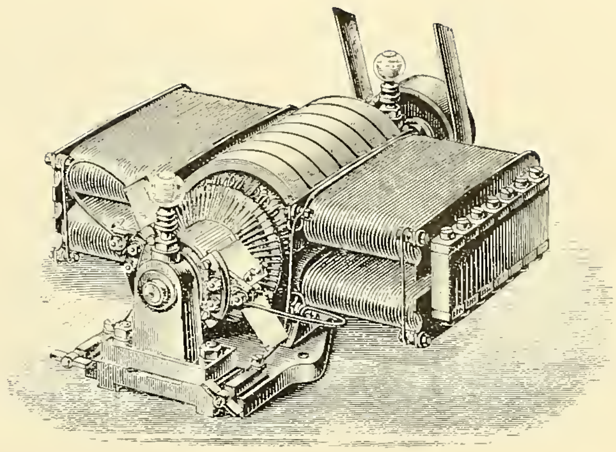


Figure 75.—The Siemens and Halske dynamo of 1876. From J. Dredge, *Electric Illumination*, London. n.d. (about 1882), vol. 1, p. 280.

TABLE 4.—*Shoolbred's comparison of three models of the Siemens machine and three models of the Gramme* type d'atelier, *1878.*

Machine and model	*R.p.m.*	*Candles*	*Hp. to drive*	*Candles/Hp.*	*Weight*	*Cost(£)*
Siemens, Model A	850	1200	2	600	250	70
Siemens, Model B	650	6000	4	1500	375	112
Siemens, Model C	360	14000	8	1750	1150	250
Gramme, Model M	1600	2000	1. 5	1333	150	70
Gramme, Model A	900	6000	2. 5	2400	375	100
Gramme, Model C	700	15000	5	3000	800	300

TABLE 5.—*Evaluation of the Siemens and Gramme dynamos at Chatham, England, in 1879.*

Machine and model	*R.p.m.*	*Candles*	*Hp. to drive*	*Candles/Hp.*	*Cost (£)*	*Efficiency (%)*
Siemens, Model B, two	680	19140	13. 4	1430	244	73
Gramme, Model A, two	875	18300	9. 6	1920	160	88
Gramme, Model C	1200	19500	9. 5	2050	240	85
Gramme, Model D	500	27500	15. 1	1820	360	89
Gramme, Model D	475	22500	12. 7	1770	360	88

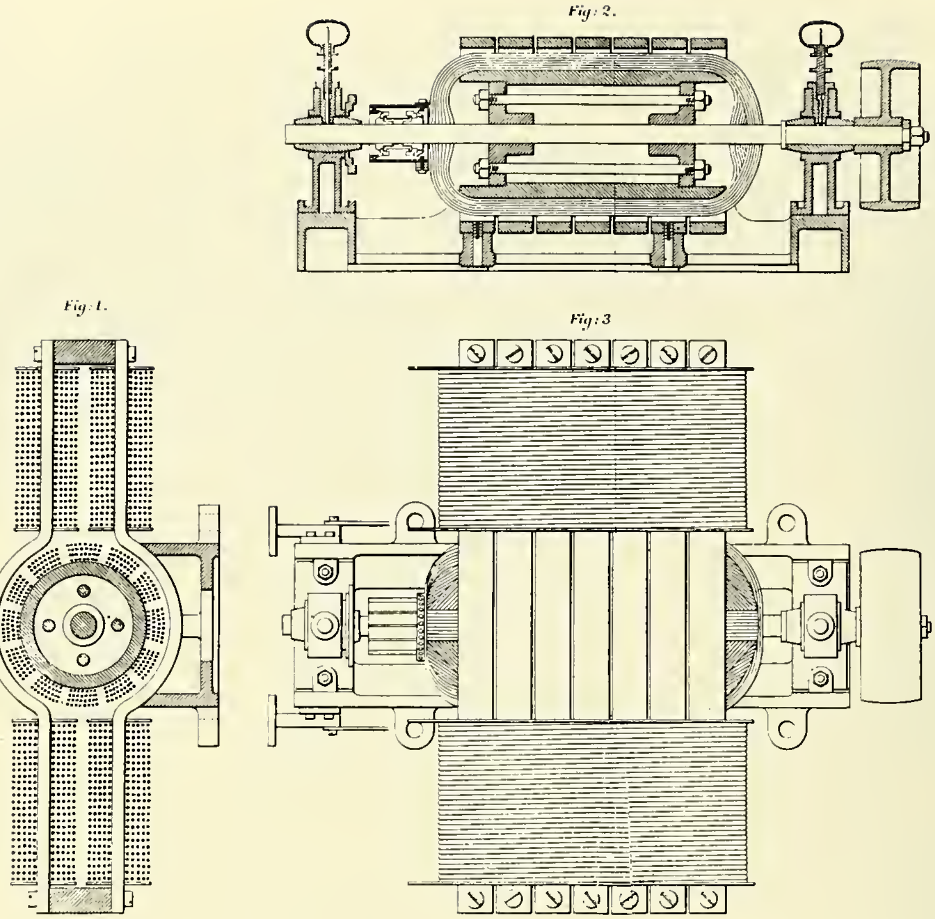


Figure 76.—Details of the Siemens and Halske dynamo of 1876. For clarity, the brushes have been omitted in the drawing. From R. W. H. P. Higgs and J. R. Brittle, "Some Recent Improvements in Dynamo-Electric Apparatus," *Minutes of the Proceedings of the Institution of Civil Engineers*, 1878, vol. 52, pp. 36–98, pl. 1.

of the Gramme dynamos is quite close to that of the Siemens dynamo as measured by Hopkinson and others.

Up to this point, three-quarters of the way through the 19th century, the electric light was possible, but it was not very practical commercially. Serrin's regulator could be used but it was so delicate that adjustment was difficult, and it was both mechanically and electrically complicated. Only one arc lamp could be used as a load in the circuit of the generators then in use; to place two regulators in the same circuit would, in effect, prevent either one from working. Moreover, the arc light was too bright for any purpose other than illuminating large areas, some means had to be found of "subdividing" it so that the brilliancy of a single arc lamp in a single circuit could be spread over many lamps of weaker intensity in the same circuit. Practical electrical generators had been invented, but the initial expense of plant installation—which was that of a gas or steam engine plus the electrical generator and the other electrical equipment that could only be used for a single light—was prohibitive for ordinary purposes (figs. 78, 79). Some means had to be found whereby such a large capital investment could be used for a number of lights that would be of lesser intensity than

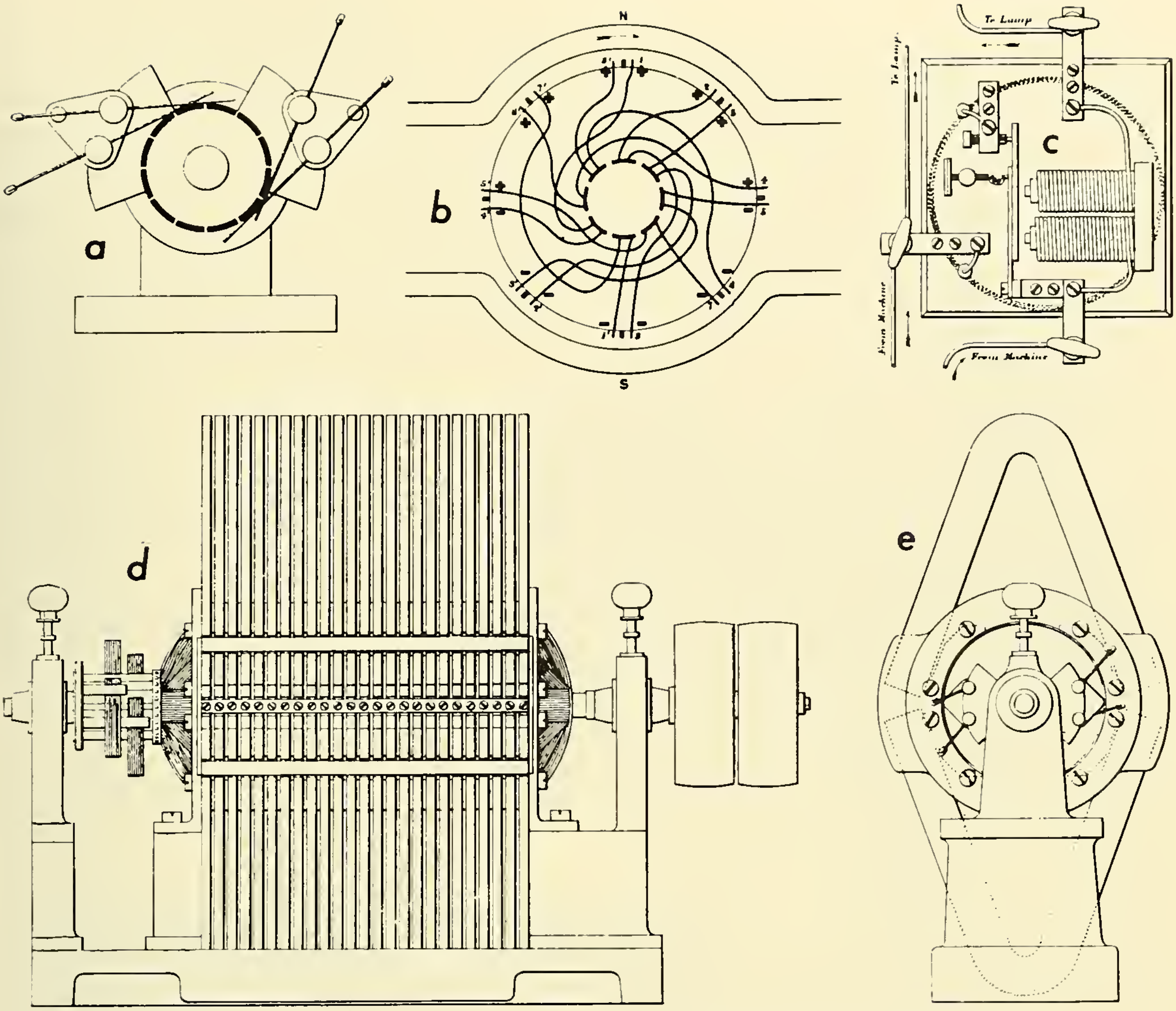


Figure 77.—*a*, Brushes and commutator; *b*, armature connections, and *c*, output regulator for the Siemens and Halske dynamo of 1876; *d, e*, views of a Siemens and Halske motor of the same date with a permanent magnet field and drum armature. From R. W. H. P. Higgs and J. R. Brittle, "Some Recent Improvements in Dynamo-Electric Apparatus," *Minutes of the Proceedings of the Institution of Civil Engineers*, 1878, vol. 52, pp. 36–98, pl. 1.

the current form of the arc light and that would all be on the same circuit. This was the problem of the subdivision of the electric light.

The first significant step towards the solution of this problem was made by a Russian military engineer named Paul Jablochkoff.[108] He had retired from the army in order to devote himself to the invention of an electrical light and decided to visit the Philadelphia Centennial Exposition of 1876. However, he tarried in Paris in order to visit Bréguet's electrical shop, where both Gramme dynamos and Serrin regulators were constructed; and he was so fascinated by what he saw that he never finished his journey. Instead, he found employment at Bréguet's

[108] "Jablochkoff," *La Grande Encyclopédie*, Paris, n.d., vol. 20, p. 1152; *Electrician*, London, 1894, vol. 32, pp. 663–664.

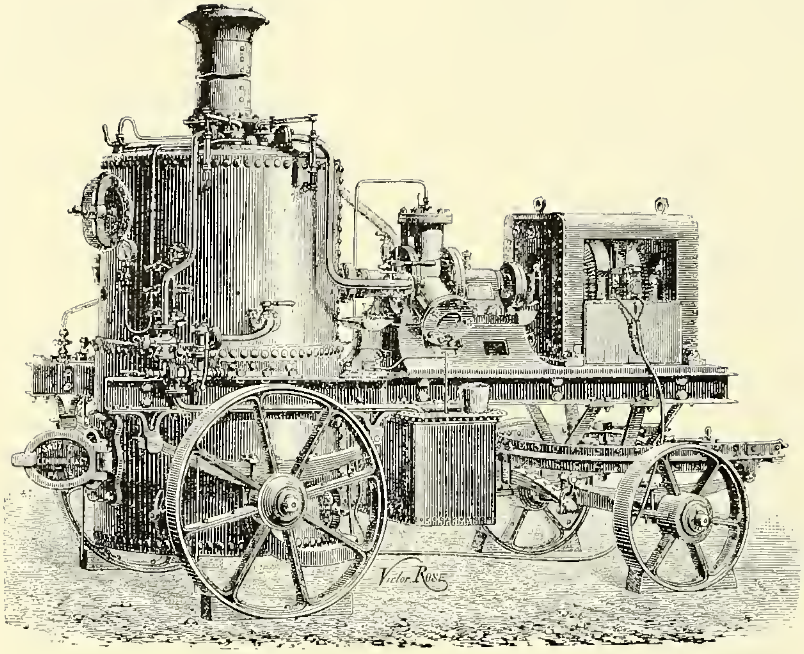


Figure 78.—Mobile arc-light unit, using a Gramme generator. From *Chronique de l'industrie*, 1879, p. 93.

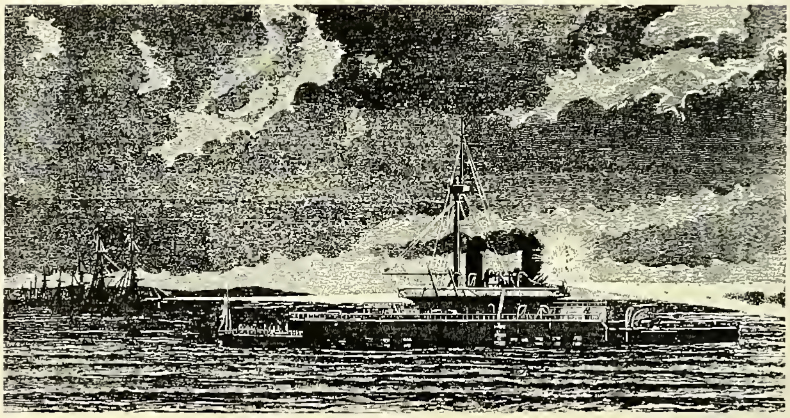


Figure 79.—Arc light on HMS *Thunderer*. From *La Lumière électrique*, October 1882, vol. 7, p. 347.

shop and stayed there for a number of years. After patenting a novel kind of electromagnet, he turned to the electrical lamp, and the innovations he introduced gave a tremendous impetus to the commercial application and exploitation of the dynamo.

Jablochkoff found a means of producing a carbon arc that regulated itself without the use of any mechanism.[109] He based his lamp (called a "candle") on the circumstances that if two carbons are placed side by side and parallel to one another, and so close that an arc could form at the ends, it would continue to burn until the carbons were entirely consumed. An insulating material—first kaolin and then a mixture of barium and calcium sulphates—was used to separate the two electrodes. The role of the spacer, called a "colombin," is not clear; apparently it provided some of the glow, and perhaps it reduced the voltage necessary to maintain the arc. Direct current was first tried, but since the positive electrode in an arc burns twice as fast as the negative, alternating current was used to make both burn at an equal rate. Each "candle" provided a light equal to that from 200 to 500 standard candles, depending on the generator and the particular circuit (fig. 80).

With this device, Jablochkoff solved two of the problems of the subdivision of the electric light—that of placing several lights in the same circuit and that of reducing the intensity of the arc light. Although the "candles" flickered somewhat and only lasted for one or two hours, the light was whiter and brighter than that from gas, and it was not as blinding as that from the ordinary arc light. As used in an onyx globe (fig. 81), it gave a broad and diffused glow that seemed to have been occasionally on the pinkish side. Since there was no mechanism to be constantly fluctuating in the circuit and causing unstable operation of the other lamps, several "candles" could be placed in a single circuit. To further increase the subdivisibility of a circuit of electric "candles," Jablochkoff first tried to use condensers and then

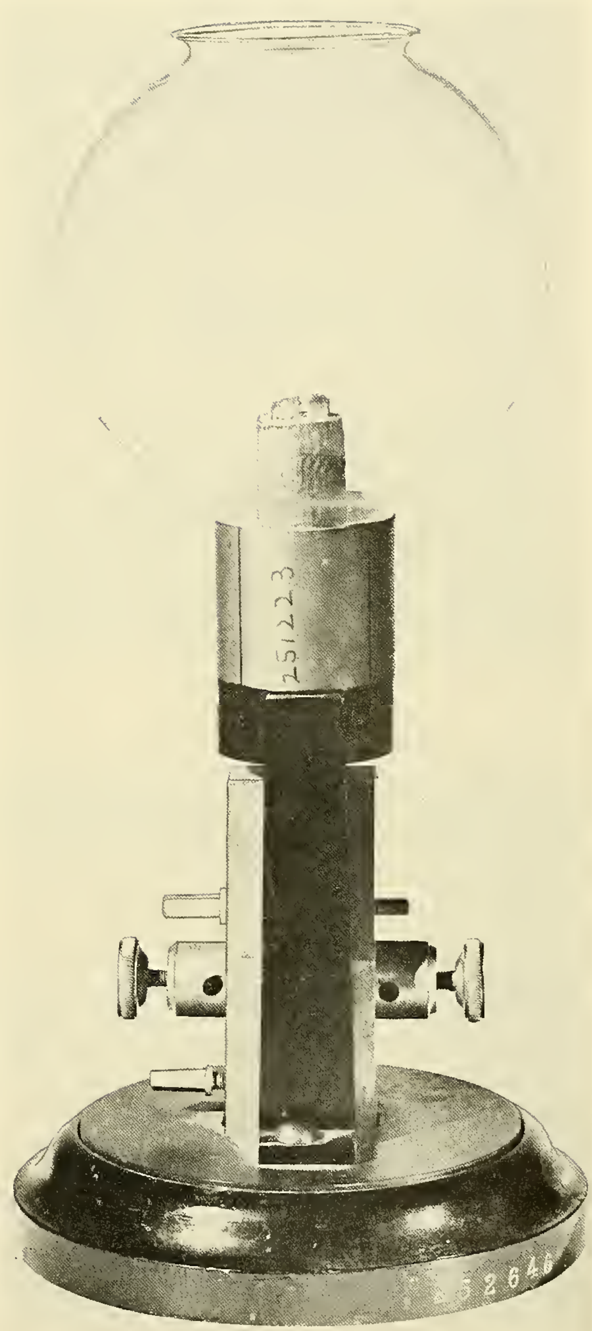


Figure 80.—U.S. Patent Office model of the Jablochkoff candle. (*USNM 252646, Smithsonian photo* 8899–*A*.)

[109] French patent 112024 (filed March 23, 1876; additions, September 16, October 2, October 23, November 21, 1876, March 31, 1877, March 11, 1879); British patent 3552 (September 11, 1876); L. Denayrouze, "Sur une Nouvelle Lampe électrique imaginée par M. Jablochkoff," *Comptes rendus*, 1876, vol. 83, pp. 813–814; Du Moncel, *op. cit.* (footnote 80), vol. 5, pp. 472–475, 515–518; *Engineering*, 1878, vol. 26, pp. 125–127; William E. Langdon, "On a New Form of Electric Light," *Journal of the Society of Telegraph Engineers*, 1877, vol. 6, pp. 303–319.

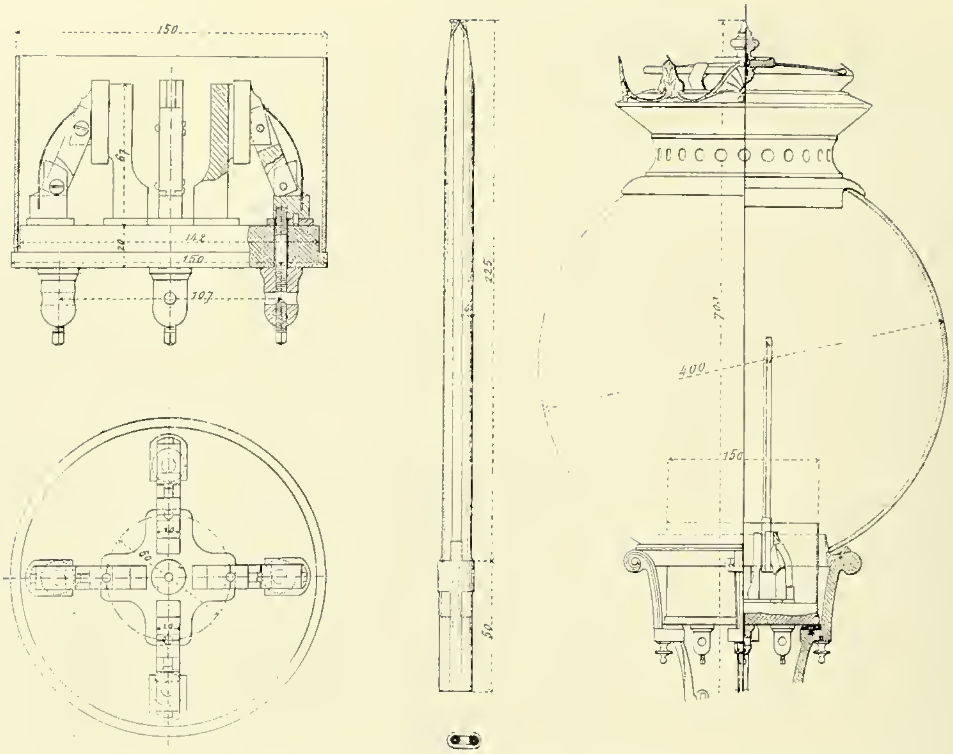


Figure 81.—Drawing of the Jablochkoff candle, candle holder, and onyx globe. As each candle was consumed, another of the four candles in the base was manually switched into position. From *Review industrielle*, June 5, 1878, p. 223.

transformers (fig. 82) in the circuit, but he found no definite advantages.[110] The primaries of the transformers were strung in series in the circuit of the generator and the "candles" were similarly placed in series in the secondaries of the various transformers.

The Jablochkoff "candle" made possible the first electric illumination on a broad commercial scale.

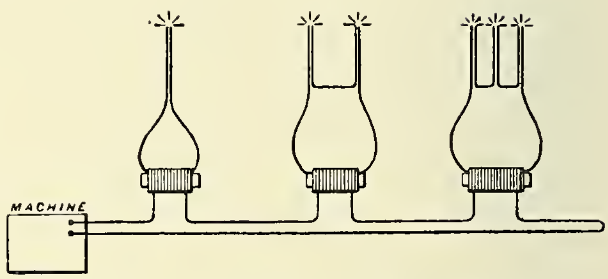


Figure 82.—Circuit diagram showing how Jablochkoff used transformers for the subdivision of his electric lights. From *Engineering*, October 14, 1881, vol. 32, p. 391.

[110] L. Denayrouze and P. Jablochkoff, "Divisibilité de la lumière électrique," *Comptes rendus*, 1877, vol. 84, pp. 750–752; P. Jablochkoff, "Application des bouteilles de Leyde de grande surface pour distribuer en plusieurs points l'effet du courant d'une source unique d'électricité avec renforcement de cet effet," *Comptes rendus*, 1877, vol. 85, pp. 1098–110; British patent 1996 (May 22, 1877); French patent 120684 (October 11, 1877; addition, October 12, 1878); *Engineering*, 1881, vol. 32, p. 391.

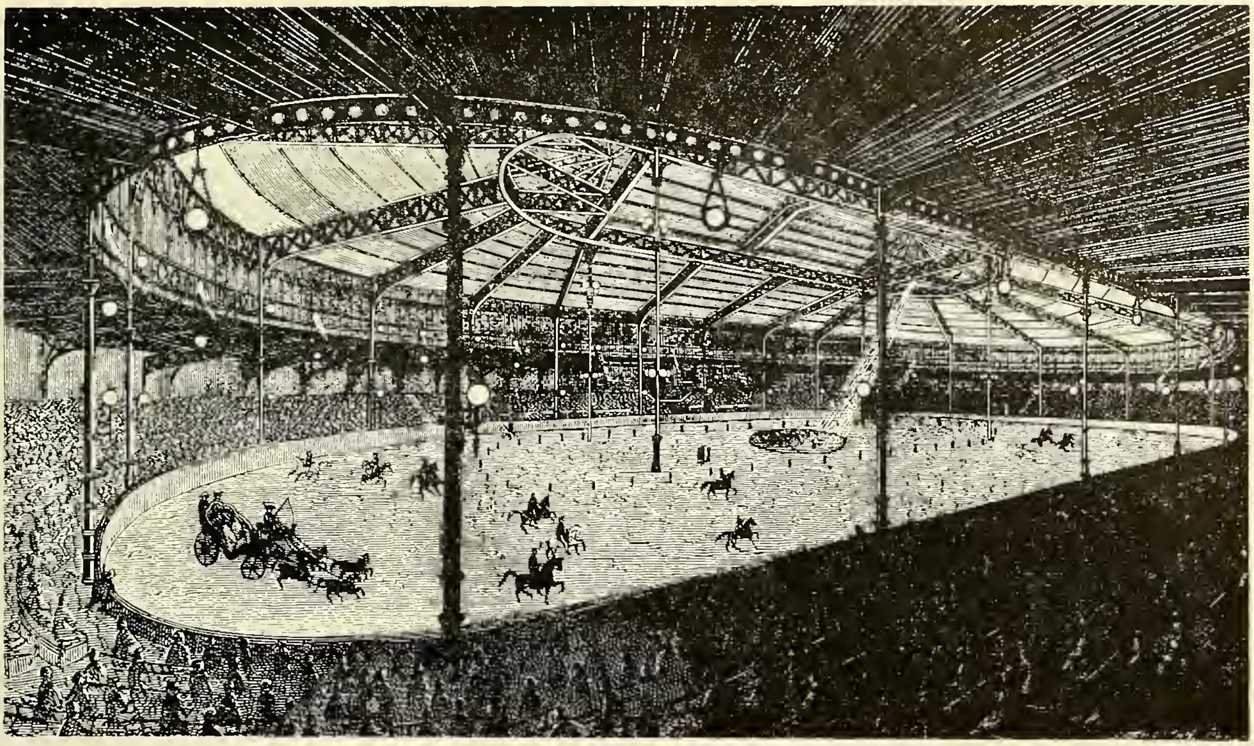


Figure 83.—The interior of the Hippodrome in Paris as lighted by Jablochkoff candles. From E. Alglave and J. Boulard, *The Electric Light*, translated by T. Sloane, New York, 1889, p. 104, fig. 66.

Figure 84.—Avenue de l'Opéra in Paris as illuminated by Jablochkoff candles in 1878. From *La Lumière électrique*, 1881, vol. 4, p. 186.

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Fig. 1.

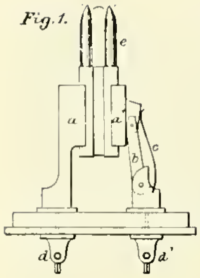


Fig. 2.

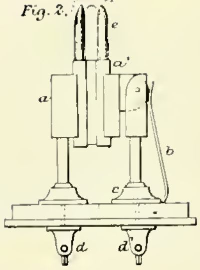


Fig. 3.

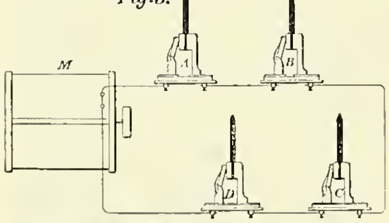


FIG 4

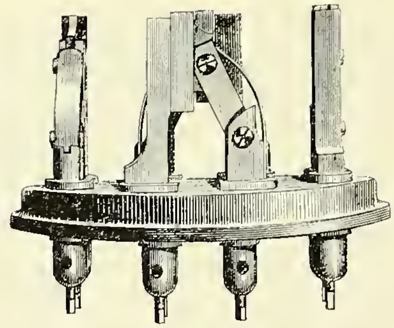
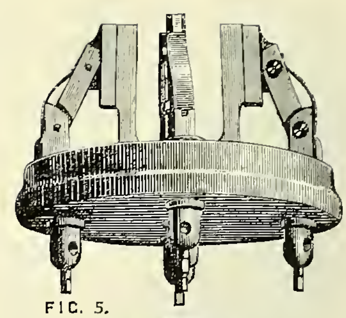
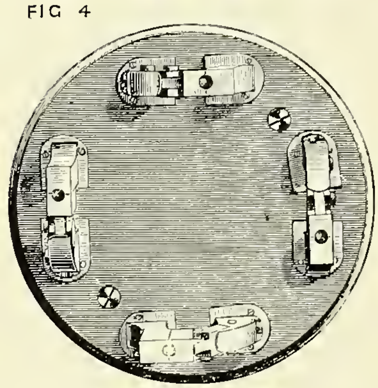
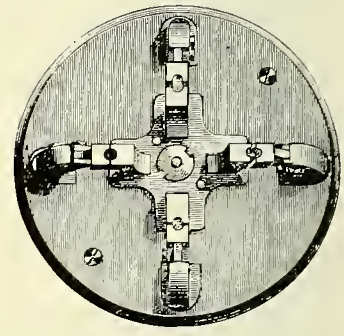


FIG. 5.







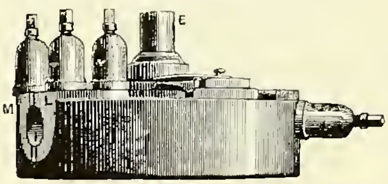


FIG. 6.

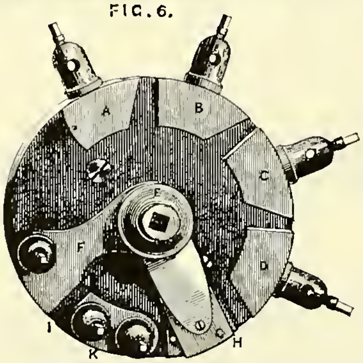
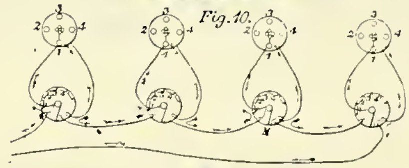


Fig. 10.



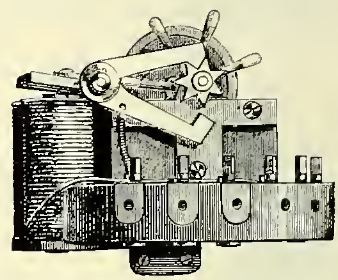


FIG. 11

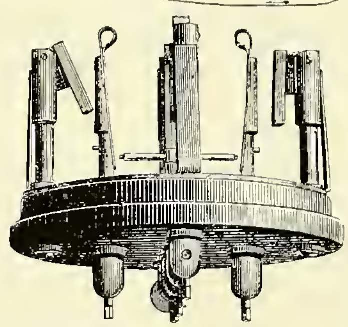
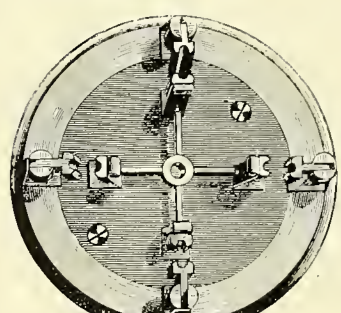


FIG. 12.



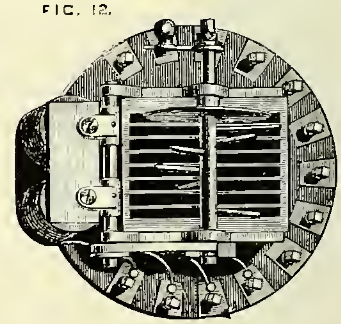


Fig 7. Fig. 8.

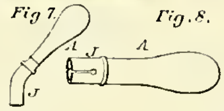
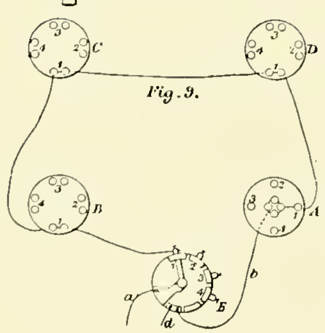


Fig. 9.



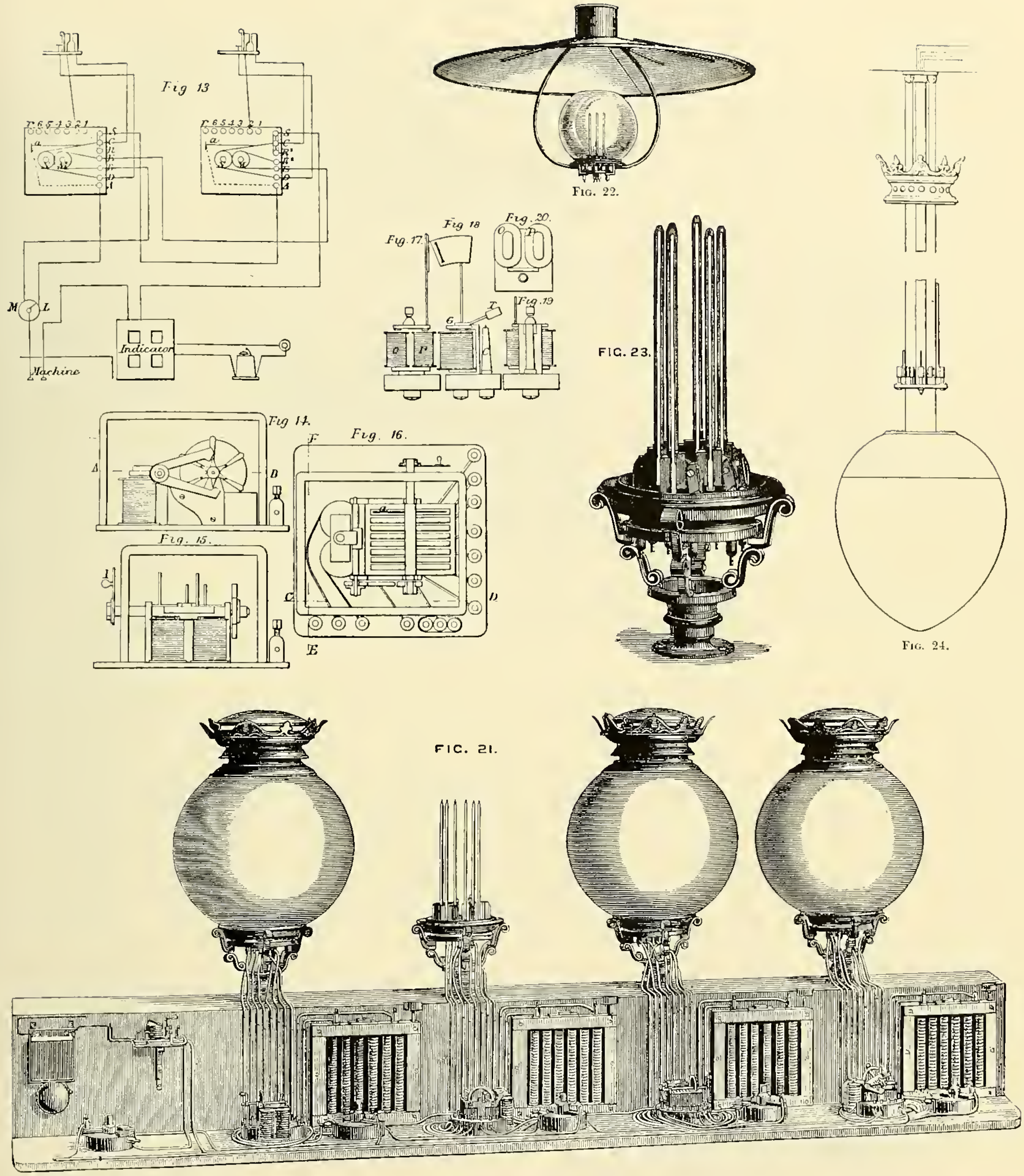


Figure 85.—The Jablochkoff system of electric lighting as applied in London in 1881. Automatic switches connected another candle into the circuit when one burned out. From *Engineering*, September 23, 1881, vol. 32, pp. 300, 301.

Fig 1. Coupe ABC.

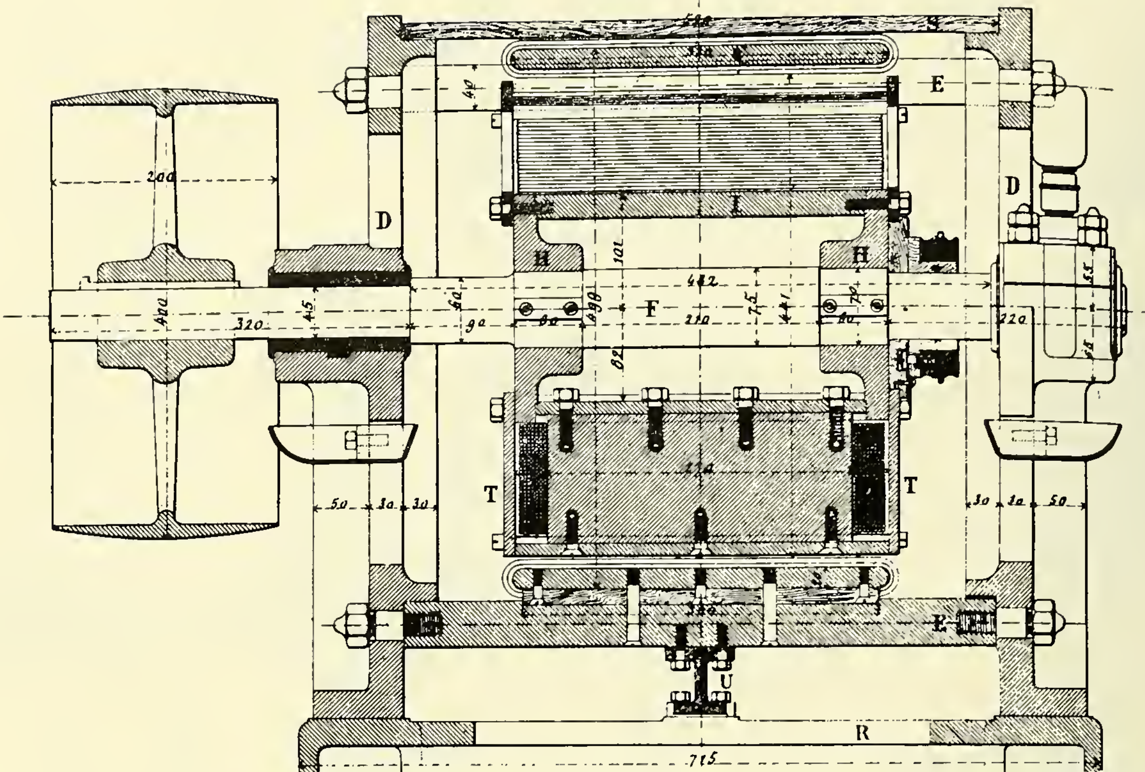
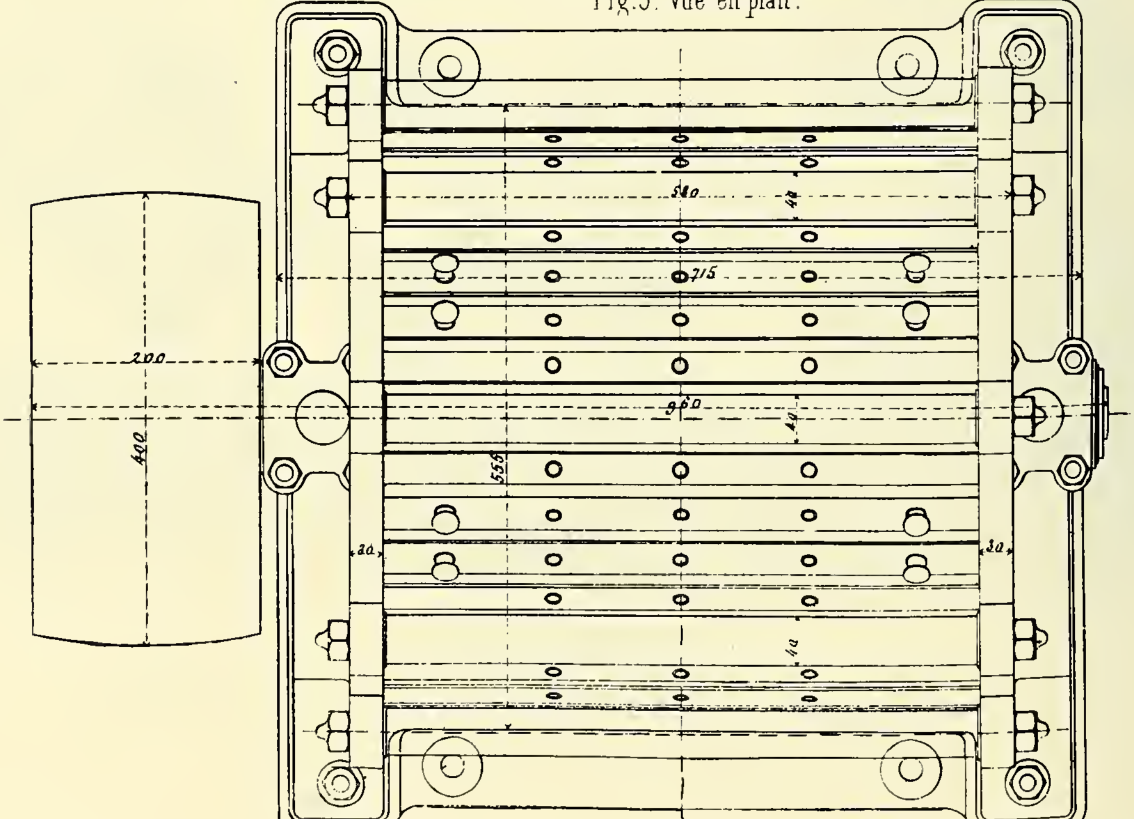


Fig. 3. Vue en plan.



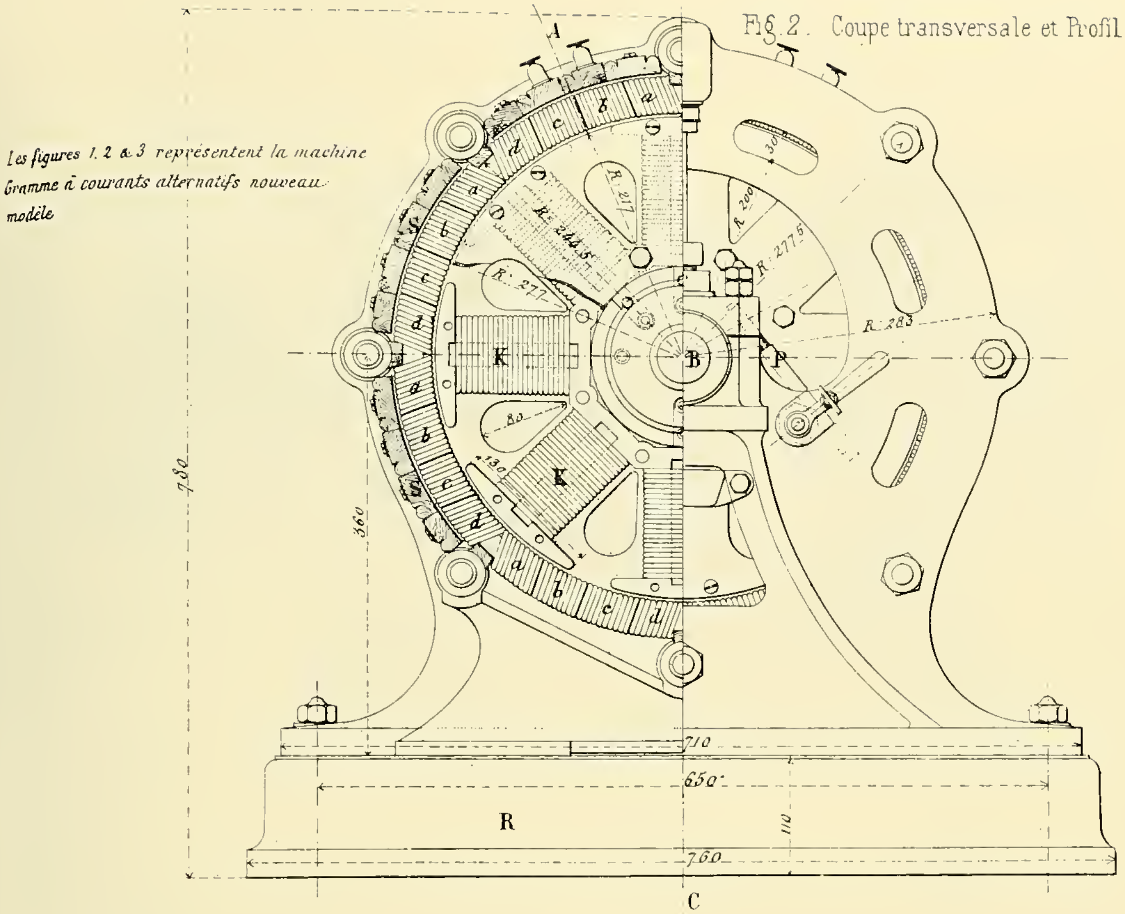
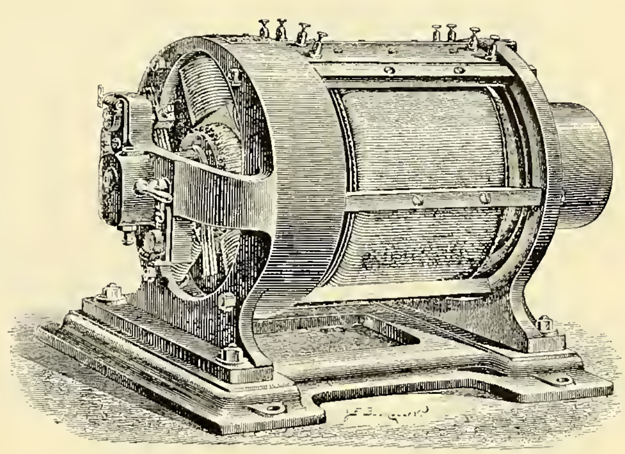
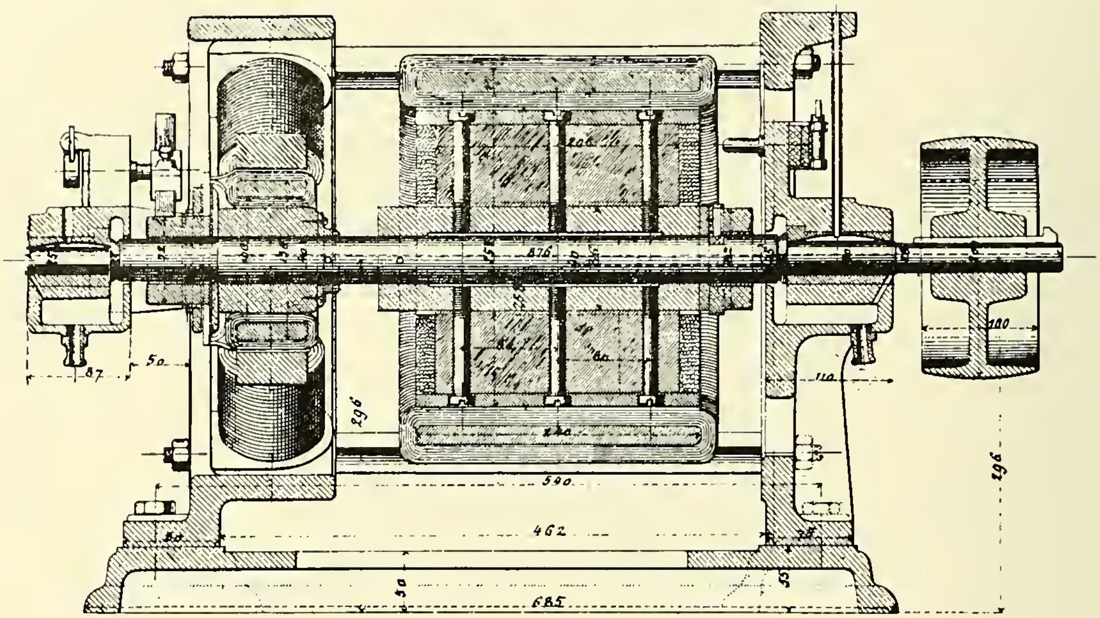


Figure 86.—*On facing page and above:* Gramme's alternator of 1878 for a 4-circuit Jablochkoff candle system, with four candles per circuit. The current for the rotating field was supplied by a separate *type d'atelier* exciter. From *Revue industrielle,* June 5, 1878, pp. 226–227, pl. 12.

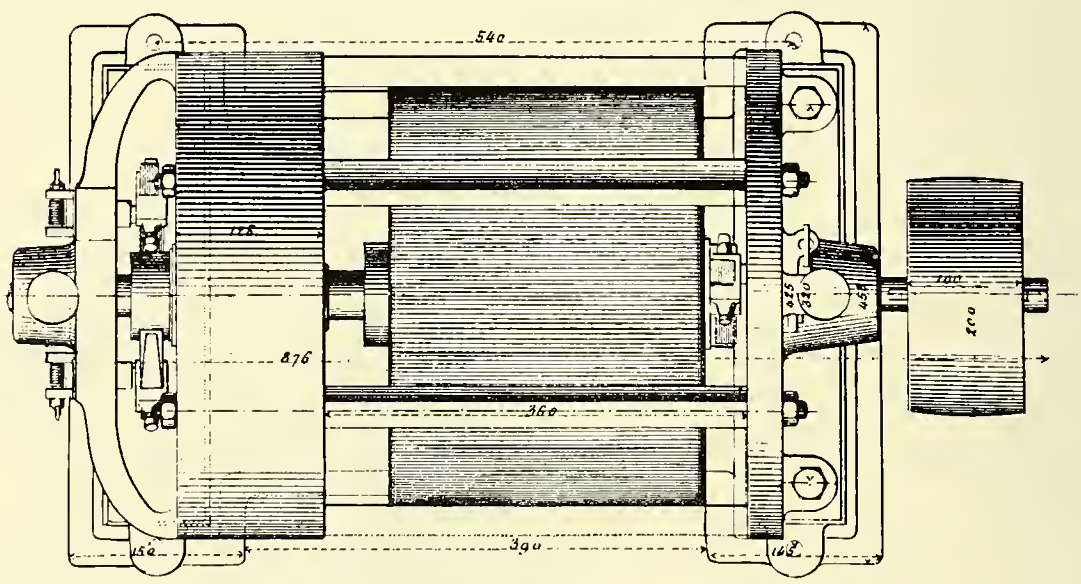
Figure 87.—Gramme's self-excited alternator (1880) for the Jablochkoff candle system. From *Revue industrielle,* February 11, 1880, p. 53.



Coupe longitudinale



Plan.



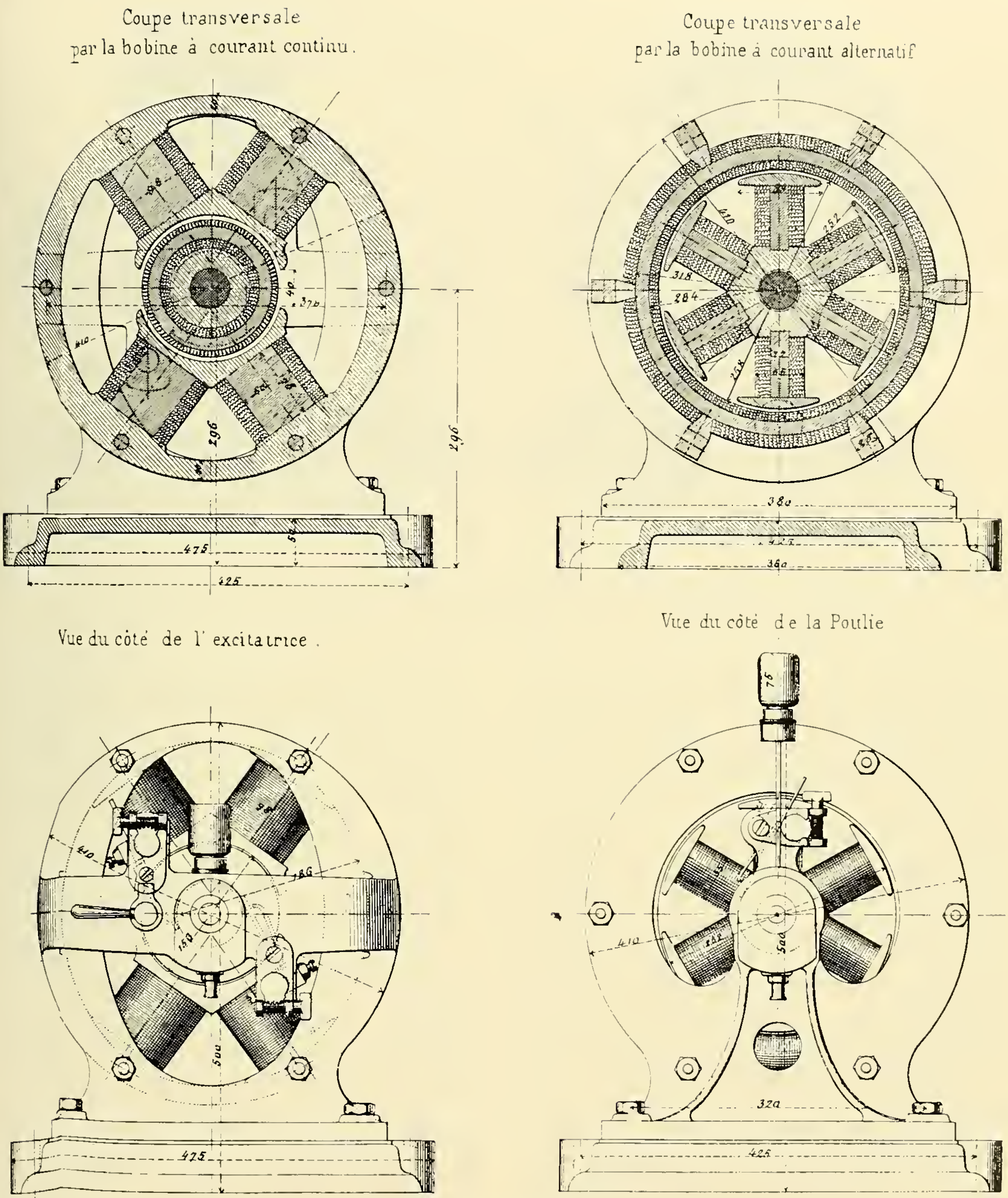


Figure 88.—*On facing page and above:* Details of Gramme's self-excited alternator of 1880. From *Revue industrielle*, February 11, 1880, pp. 56–57, pl. 3.

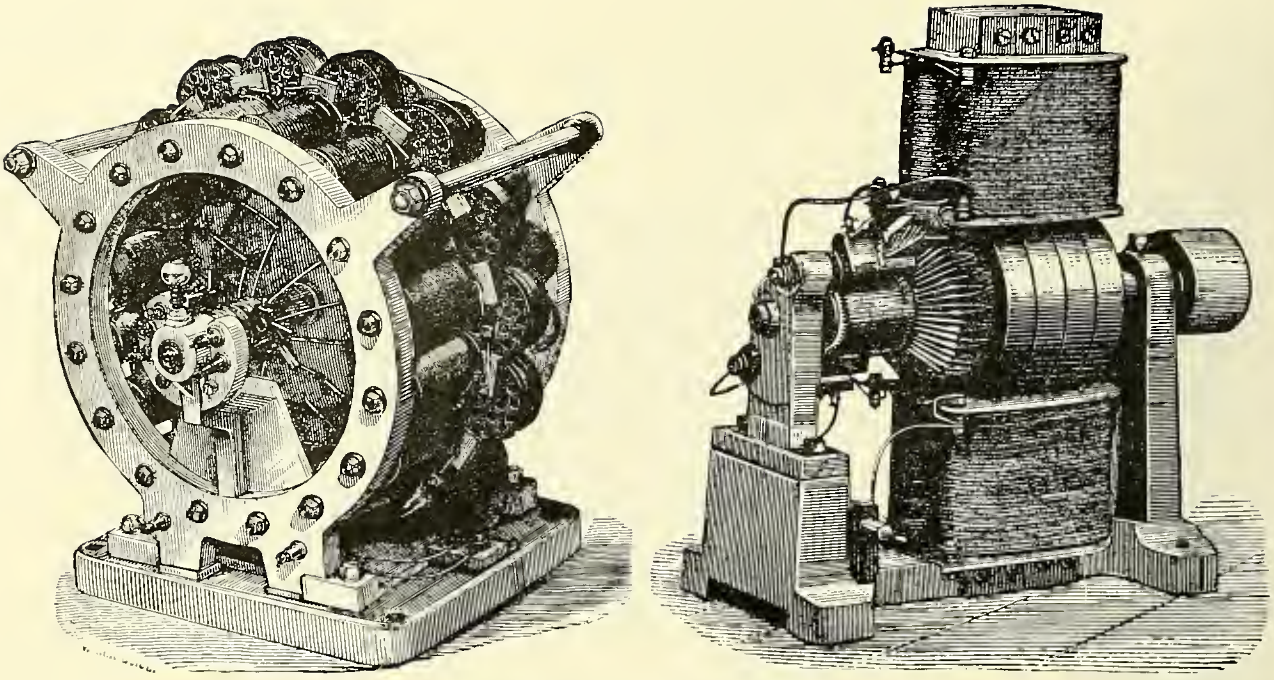


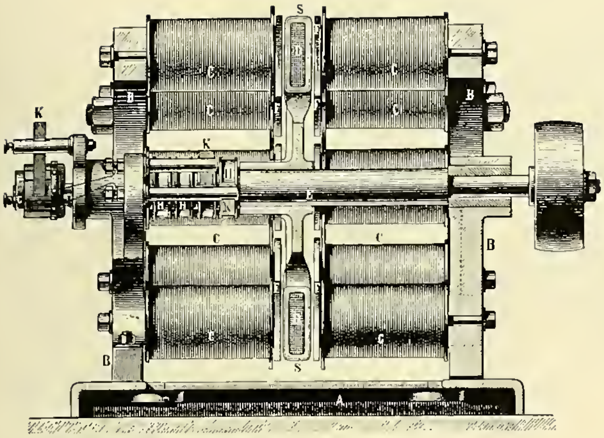
Figure 89.—Siemens' alternator (left), and separate exciter, for use in a Jablochkoff candle system. From J. Dredge, *Electric Illumination*, London, n.d. (about 1882), vol. 1, figs. 272, 273.

In April 1877, 16 of the "candles" were placed in the Grands-Magasins du Louvre in Paris. The Parisian Hippodrome followed a short time later with a system that included both Serrin regulators and Jablochkoff "candles"; however, this system was installed by Hippolyte Fontaine instead of Jablochkoff's Société Générale d'Electricité (fig. 83). Electric illumination moved from the laboratory to the stock market when the Avenue de l'Opéra and the Place de l'Opéra were lighted by 62 of these new devices in May 1878 for the Paris Universal Exhibition of 1878 (fig. 84). The grand total of some 300 "candles" along the boulevards and in public buildings made apparent to all the newest of the wonders of electricity; accordingly, the price of gas stocks dropped 10 percent. In December 1878 the Municipal Council of Paris decided to try the "candles" for public illumination, in competition with gas, for one year.[111]

[111] *Les Mondes*, 1877, vol. 42, pp. 709–710; 1879, vol. 48, pp. 221–222; *Engineering*, 1877, vol. 23, pp. 366, 384–385; 1878, vol. 26, pp. 24, 479; 1879, vol. 27, pp. 104–105, 415; *La Lumière électrique*, 1880, vol. 2, pp. 229–230, 301–305; 1881, vol. 4, pp. 185–188; *Revue industrielle*, 1877, p. 369; Fontaine, *op. cit.* (footnote 19), pp. 215–216; Defrance, op. cit. (footnote 2).

London imitated the example of Paris a short time later. After trying the Jablochkoff system on an experimental scale at Billingsgate Market, in December 1878 the municipal government installed 20 "candles" along the Thames Embankment and 16 along the Holborn Viaduct; they were placed about 50 yards apart. The system proved to be so satisfactory that, in May 1879, 20 more "candles" were added along the Embankment, and in October of the same year 10 were placed on Waterloo Bridge. By 1880 subdivision of the electric light had proceeded to the point that a single central power station at Charing Cross fed over 75 "candles" in one system that extended 1 mile northeast along the Thames Embankment to Waterloo Bridge and Holborn Viaduct and in another that extended 1 mile southwest to Victoria Station.[112] The mechanical and electrical details of the system were further refined during the following year (fig. 85).

[112] *Engineering*, 1878, vol. 26, pp. 494; 1880, vol. 29, p. 268; *Revue industrielle*, 1880, vol. 9, p. 148; Berly, "Notes on the Jablochkoff System of Electric Lighting," *Journal of the Society of Telegraph Engineers*, 1880, vol. 9, pp. 135–161.



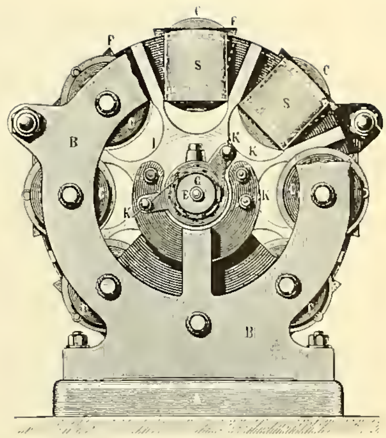


Figure 90.—Two views of Siemens' self-excited alternator of 1882. From J. Dredge, *Electric illumination*, London, n.d. (about 1882), vol. 1, figs. 274, 275.

At first the Alliance machine was used to supply the power, and this allowed the now rather moribund Société l'Alliance to continue its existence. However, it was soon found that the Gramme generators were more efficient.[113] In addition, with his usual ingenuity, in 1878 Gramme devised alternating current generators for 4, 16, and later 32 "candles" (fig. 86).[114] One *type d'atelier* dynamo was used to provide the current for the electromagnet field coils of one or more alternators. These last had a rotating field, with 8 radial poles, and a stationary armature. The coils were grouped on the stator so that a number of circuits (normally with four "candles" per circuit) could be taken off a single alternator. Each "candle" provided about 100 Carcel units, and, as the following tabulation shows, each consumed about 1 hp.:

Candles	Length/width/height (cm.)	Weight (kg.)	R.p.m.	Hp.	Cost (£)	Cost (francs)
16	89 x 86 x 78	650	600	16	400	10, 000
6	70 x 40 x 52	280	700	6	200	5, 000
4	55 x 40 x 48	190	800	4	100	2, 500

Two years later, in 1880, Gramme devised his *machine auto-excitatrice*, which combined both the alternator of 1878 and a 4-pole dynamo within a single frame (figs. 87, 88).[115] Two sizes were manufactured—a small model weighing 280 kg. and requiring 4 hp. to supply 12 "candles," and a large one weighing 470 kg. and requiring 8 hp. to supply 24 "candles." The light from each "candle" was from 20 to 30 Carcel units. Apparently this *machine auto-excitatrice* was not patented.

The Siemens dynamos also were used in the Jablochkoff system to excite the Gramme alternator. However, it was not long before the Siemens firm had designed its own alternator (fig. 89) and had a Paris agent who supplied it in quantity. The construction of the Siemens alternator was essentially that of the Woolrich machine, with electromagnets substituted for the permanent magnets and with a disk armature rotating between two stationary rings of electromagnets.[116] Depending on the size of the machine, there

[113] *Les Mondes*, 1877, vol. 42, pp. 346–347; vol. 43, p. 779.

[114] French patent 120649 (October 23, 1877; additions, December 3, 1877, and September 1, 1879); British patent 953 (March 9, 1878); *Revue industrielle*, 1878, vol. 7, pp. 222–224; *Engineering*, 1878, vol. 26, pp. 63–66; 1881, vol. 32, pp. 251–253, 275–277, 299–302, 326–329, 353–355; Fontaine, *op. cit.* (footnote 19), pp. 161–166.

[115] *Revue industrielle*, 1880, vol. 9, pp. 53, 56–57: *La Lumière électrique*, 1880, vol. 2, pp. 88–89; *Engineering*, 1880, vol. 29, p. 136.

[116] German patents 2245 (March 9, 1878) and 3383 (April 3, 1878); French patents 123307 (March 20, 1878) and 12479 (May 27, 1878); British patent 3134 (August 8, 1878); *La Lumière électrique*, 1879, vol. 1, pp. 25–26; *Engineering*, 1879, vol. 27, pp. 181–182.

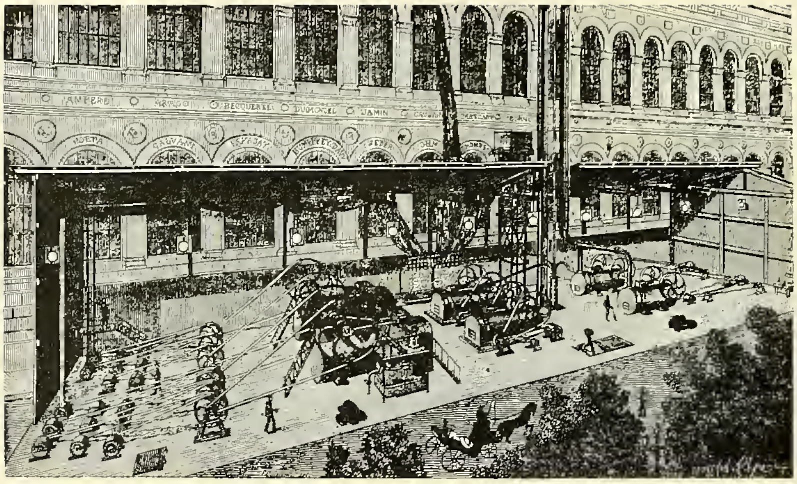


Figure 91.—Central station of Jablochkoff electric light system (1880) for illuminating an exposition of paintings in Paris. From *La Lumière électrique*, June 15, 1880, vol. 2, p. 228.

were 8 or 16 electromagnets in each of the stationary rings and in the disk armature. The alternator was constructed in three sizes—4-, 8-, and 16-light machines that, with their exciters, required, respectively, 4, 7, and 13 hp. The smallest machine was cited as providing a light of 300 candles from each of the four "candles." The Siemens firm also manufactured a self-excited alternator (fig. 90).

For a while it seemed as if the Jablochkoff system might be the solution to the problem of the electric light. During the next few years its application expanded quite rapidly; in addition to its use in cities (figs. 91, 92) it was utilized to light the cabins of ships. But the sudden rise of this new device came to an almost equally as sudden halt as more economic means of subdividing the electric light were developed.

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