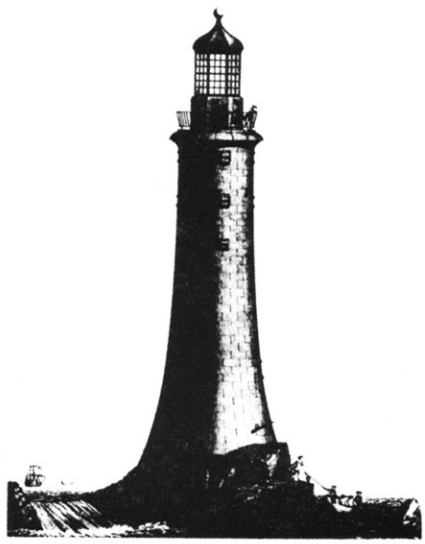
should be used. First, he found that the use of lime made from "imperfectly burnt" stone was wasteful. Second, he found that the hardness of the stone from which lime was made had no relation to the hardness of the mortar produced—an erroneous assumption that went back to the writings of Vitruvius. He tested a variety of stones in turn as sources of lime. Tests were made on mortar also containing pumice stone, coal cinders, brick and tile dust, scale from smiths' forges, and several other substances that were sometimes employed to impart hydraulic properties to mortar. The most effective proved to be tarras and pozzolana. After different mixtures of the mortar ingredients had been tested, Smeaton estimated their cost per cubic foot. Tarras would have been the choice because of cost, except for an unforeseen circumstance:



> In making enquiries how some [pozzolana] might be procured from [Italy], I very fortunately learnt, that there was a quantity of it then in the hands of a merchant in Plymouth; which had been imported as an adventure from Civita Vecchia during the time Westminster Bridge was building; and which he expected to have disposed of for that work to a good advantage; but failed in his speculation: for having found that tarras answered their purpose, neither Commissioners, Engineers, nor Contractors, would trouble themselves to make a trial of it [pozzolana], and therefore refused it.[3]

A low price quoted by the merchant made pozzolana Smeaton's choice, for with lime from Aberthaw's blue stone it would make the most economical mortar, balancing strength and cost.

In his experiments Smeaton had found that hydraulic cement depended on "a considerable quantity of clay" being in the stone, although clay added to pure lime did not result in hydraulic qualities.[4] Without knowledge of the complex chemistry of cements, Smeaton had determined a fundamental characteristic of natural hydraulic cement by one of the earliest exhaustive studies of a building material.

For some reason Smeaton's methodical investigations in preparation for the construction of Eddystone Light were not known to Bryan Higgins, an Irish physician and chemist who operated a school of chemistry in London. After a series of carefully conducted laboratory studies he patented a form of stucco containing lime, sand, and bone-ash, a mixture he employed in several houses. But Higgins's stucco proved not to withstand weathering well, and it was overwhelmed by the competition of James Parker's Roman cement.[5]

Little is known of Parker before his 1791 patent for using peat as a fuel for burning brick or lime. Nothing came of this venture, but five years later he

obtained another patent for "A certain Cement or Terras to be Used in Aquatic and other Buildings, and Stucco Work."[6] This material, first known as "Parker's Cement" and later as "Roman cement," was made from "noddles" found at various places in England, particularly in the low cliffs where London clay reaches the shore. Known locally as cement-stones and technically as septaria, these kidney-shaped stones contain veins and a center of claylike material. To produce Roman cement they were shattered by boys wielding hammers and carried off to a bottle-shaped kiln that held about 30 tons with the coal necessary to burn it. After the kiln had been fired for about three days, the stone that had been sufficiently burned could be taken out at the bottom of the kiln and additional stone and coal added at the top.[7] The burned stone was then ground between millstones and sieved before being put in barrels for shipment.

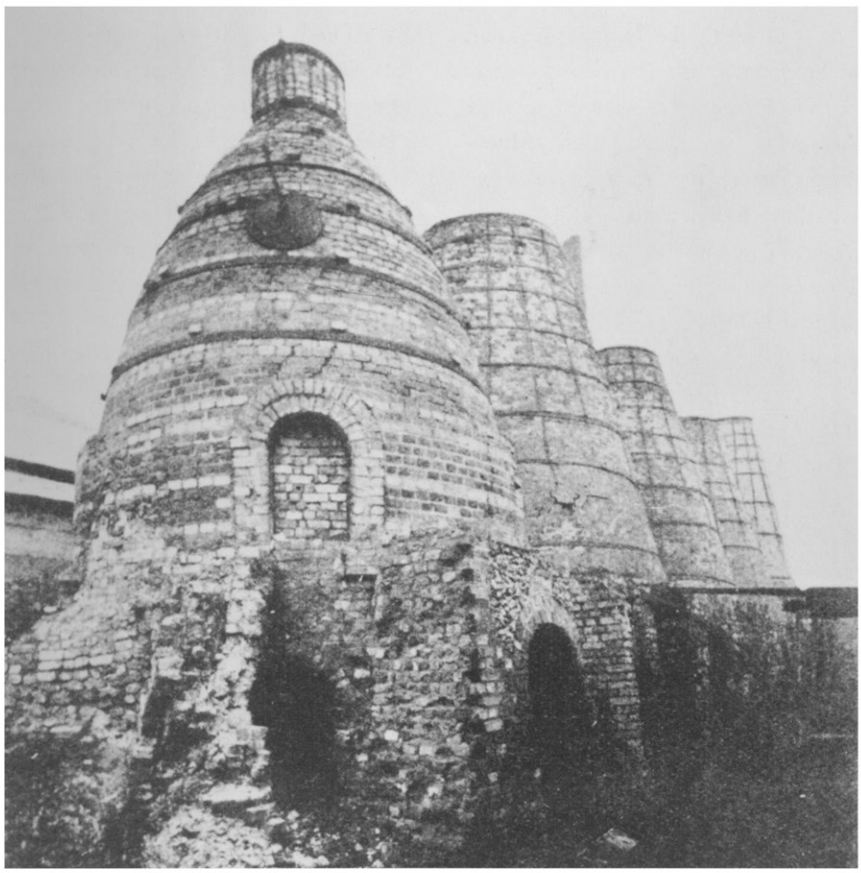
6.2 Bottle kilns such as these were filled with fuel and cement stone to produce the clinkers from which Portland cement was ground. Disadvantages of the bottle kilns were the fuel wasted in heating and cooling the mass of brick and the costly hand sorting of material when it was imperfectly fired due to variable winds about the kilns. (A. J. Francis, *Cement Industry 1796–1914*, 1977.)

Shortly after Parker received his patent, the directors of the British Society for Extending the Fisheries and Improving the Sea Coasts of This Kingdom authorized that his product be evaluated by the Society's engineer, Thomas Telford, who had considerable experience in the construction of canals and harbor facilities. Telford's report to the directors was so favorable that Parker quickly published it in a promotional pamphlet. For some reason, almost two years later Parker sold his patent to Samuel Wyatt and his young cousin Charles Wyatt. A brother of the prominent architect James Wyatt, Samuel Wyatt had become an architect after starting as a builder, and it was he who years before had experimented with the use of Higgins's stucco.[8] The Wyatt factory prospered, at least until 1810 when Parker's patent expired. Successive members of the Wyatt family inherited direction of the company, and the development of other products after 1810 suggests that their sales of Roman cement declined in the face of the competition that quickly materialized.

A British patent taken out in 1824 by a Leeds bricklayer, Joseph Aspdin, described a method of making cement and applied to this product the term "Portland cement." The use of such cement was claimed to produce a mass equal in strength and appearance to the limestone taken from quarries near the town of Portland on the southern coast of England. The modern definition of Portland cement may not be applicable to the product Aspdin patented. Portland cement today is "made by burning at a high temperature—to incipient fusion of the material—a definite mixture of limestone with clay or shale, and finely grinding the resulting clinker."[9] It is doubtful that the cement produced under the 1824 patent of Aspdin was burned at a temperature high enough to produce clinkers, and his patent does not state the proportions of the ingredients employed, so we cannot with certainty identify it as a true Portland cement by modern definition.

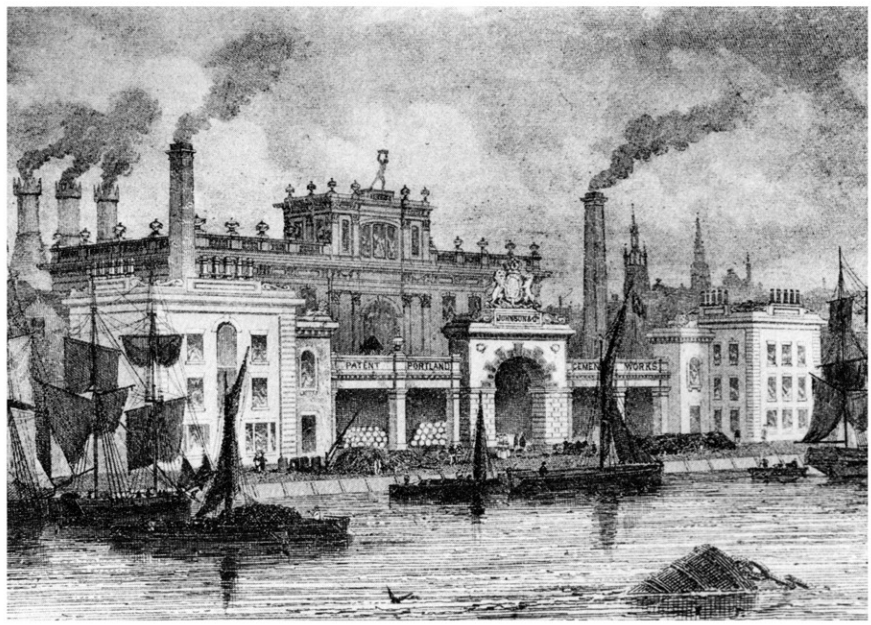
In 1825 Aspdin established a cement factory in a suburb of Leeds. The kilns used for burning the raw materials were built of masonry in the shape of a bottle, about 36 feet high and 17 feet in diameter near the bottom (fig. 6.2). Each firing required that the entire mass of brick be reheated, and certain velocities and directions of wind could result in the amount of coke consumed being well over half the weight of the clinker made. In addition, a good percentage of the product might be imperfectly burned, which would require tedious and costly inspection and sorting by hand.

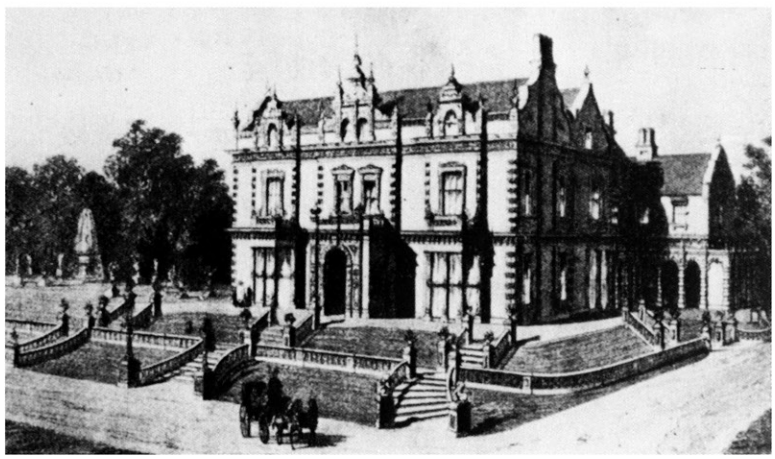
In the 1840s, controversy about cements was keen in the London area, and England led in the development of this material. J. B. White and Sons had samples of their cement tested in a 75-ton hydraulic compression

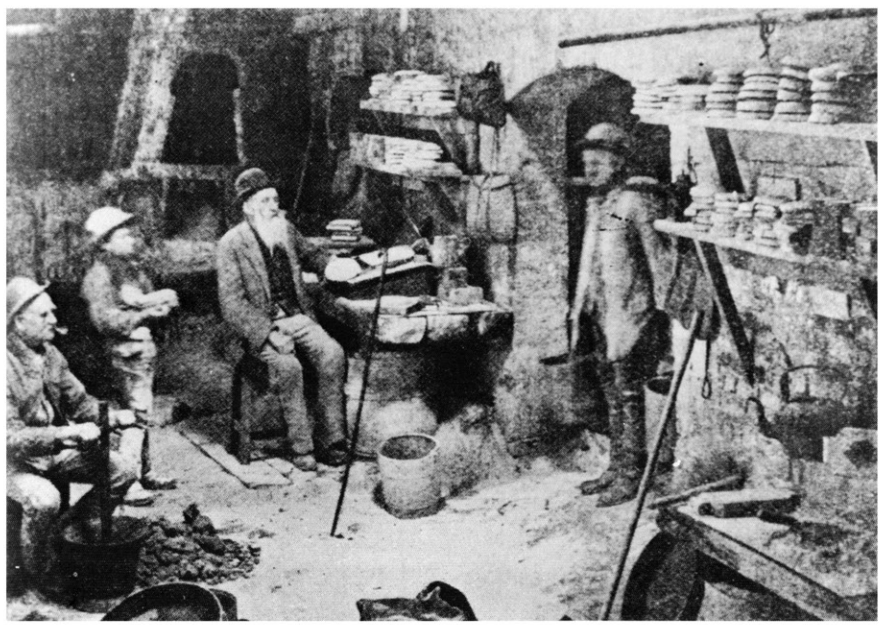


machine in 1847, and the results were published the following year in *The Builder*. Publication of these tests stirred the firm of Robins, Aspdin and Company (one of whose partners was William Aspdin, Joseph Aspdin's son) to commission and publish their own tests. The compressive strength of their cement was much higher than that for White's product. Because these tests are similar to those of tests made in 1860–1862 for the London Drainage System, which are known to represent samples of true Portland cement, it seems reasonable to assume that in 1848 Portland cement was being made by both companies, and perhaps also by the four competing cement companies in England (figs. 6.4, 6.5).

Joseph Aspdin's principal competitor for the title of "inventor" of Portland cement was Isaac Charles Johnson, who began in 1835 as manager of the J. B. White and Sons cement works. Around 1845 Johnson's employers failed in negotiating an arrangement with William Aspdin and his partner to participate in the manufacture of Portland cement. In an interview made when he was approaching seventy, Johnson clearly indicated that he had been willing to engage in a bit of early industrial espionage, and apparently William Aspdin realized the likelihood of such efforts:







There was no possibility of finding out what [Aspdin] was doing, because the place was closely built in, with walls some twenty feet high, and with no way into the works, excepting through the office. . . .

[Aspdin] had a kind of tray with several compartments, and in these he had powdered sulphate of copper, powdered limestone, and some other matters. When a layer of washed and dried slurry and the coke had been put in the kiln, he would go in and scatter some handfuls of these powders from time to time as the loading proceeded, so the whole thing was surrounded by mystery.[10]

Johnson had a chemical analysis made of Aspdin's cement but this was of little use, and a series of experimental mixtures produced no clues.

By mere accident, however, some of the burned stuff was clinkered, and, as I thought, useless. . . . However, I pulverized some of the clinker and gauged it. It did not seem as though it would harden at all, and no warmth was produced. I then made mixtures of the powdered clinker, and powdered lightly-burned stuff, which did set, and soon became hard.[11]

By the 1850s there were six companies in England manufacturing Portland cement, and it had begun to overtake the popularity of Roman cement.

After Smeaton's experiments there were many trials and many errors made by practical men, but little was done to provide a theoretical explanation of the properties of cement. A French military engineer, Louis Joseph Vicat, in 1818 published *Recherches expérimentales sur les chaux de construction, le béton et les mortiers*, an account of his studies of cements and the conclusions he had drawn from them. He was at that time directing construction of a bridge across the Dordogne River, the first large project of the period for which concrete foundations were made without the use of pozzolana.[12] Vicat had set about investigating those factors that would result in a mortar capable of setting under water. By mixing lime, chalk, and clay of different types and in different proportions, Vicat prepared small blocks of the test materials. In simplest form, his conclusion was that "no perfectly hydraulic mortar exists without silica, and all lime which can be so denominated [hydraulic] is found by chemical analysis to contain a certain quantity of clay."[13] Where Smeaton had searched for the most advantageous natural materials for a hydraulic cement, Vicat's conclusion implied that the key was in the planning of mixtures. In fact, Vicat declared that "we can give to the factitious [artificial] lime whatever degree of energy we please, and cause it at pleasure to equal or surpass the natural limes."[14]

Vicat's ability to foretell the future is remarkable. He was aware of the changes that improved knowledge of the chemistry of cement would make in the industry that supplied it:

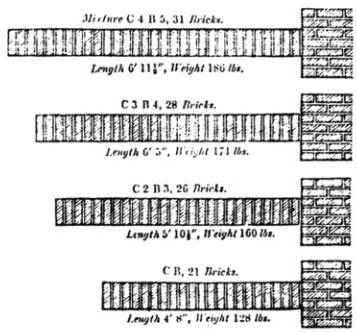
That which is in England very improperly termed Roman cement is nothing more than a natural cement resulting from a slight calcination [heating] of a calcareous mineral [limestone, chalk, or marble], containing about thirty-one percent of ochreous clay and a few hundredths of carbonate of magnesia or manganese. . . . Its use will infallibly become restricted in proportion as the mortars of eminently hydraulic lime shall become better known and in consequence better appreciated.[15]

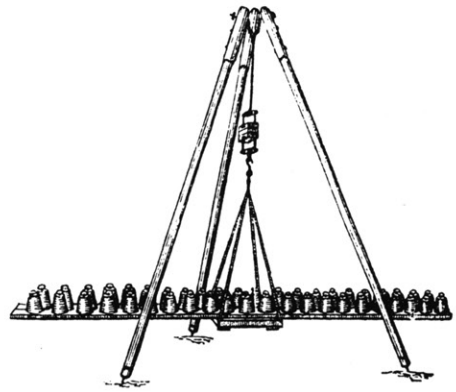
Vicat devised a method that was long used to determine the setting

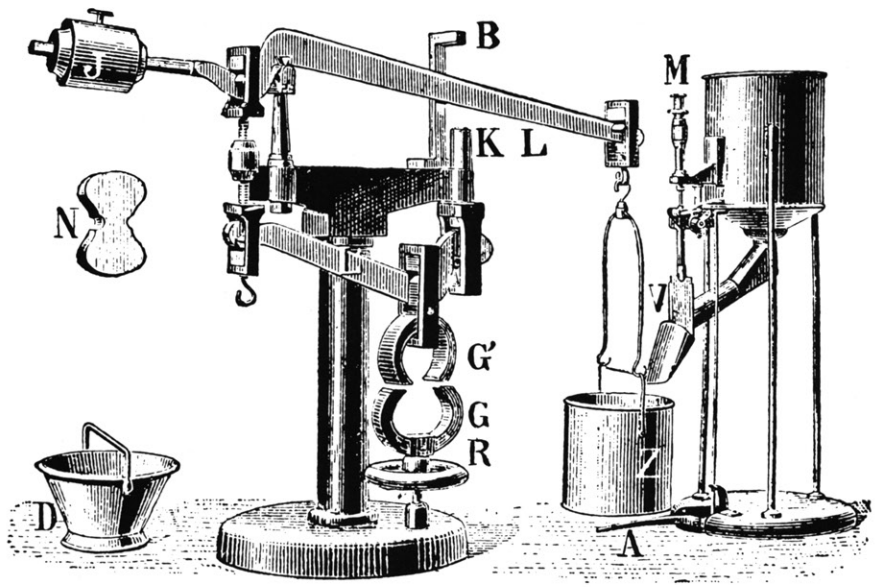
6.3 By 1843 William Aspdin, younger son of Joseph Aspdin, appears to have begun production of a true Portland cement. The nine years that followed saw Aspdin involved in a succession of partnerships and bankruptcies. With the organization of Aspdin, Ord and Company, the company was moved from London to these new buildings near Newcastle, where fuel and wages cost less. The plant was later taken over by I. C. Johnson. (Borough Library, Gateshead.)

6.4 In 1855 William Aspdin began the construction of Portland Hall at Gravesend, east of London on the Thames estuary. Coated with Portland cement stucco, the house was to have extensive gardens ornamented with statuary and architectural details made of the firm's product. After its completion, Portland Hall became embroiled in Aspdin's intricate financial crises. (Borough Library, Gravesend.)

6.5 The testing room of an English cement works in 1850, though crude by modern standards, indicates the early concern with the complex chemistry of cement. Only seven years earlier, a faulty chemical analysis of a competitor's cement had led I. C. Johnson to experiment vainly with the inclusion of burned bones in his cement. (*Journal, Portland Cement Association*, 1960. Courtesy of Blue Circle Industries, London.)







6.6 Two of the testing procedures used by Pasley were (left) adding bricks to a cantilever from a wall, each brick held in place with pressure for 5 to 10 minutes, and (right) determining the weight required to pull apart three bricks about 40 days after they were joined. In both tests, a "C4B5" mixture for the cement (4 parts of chalk to 5 parts of blue clay) was strongest. (C. W. Pasley, *Observations on Limes, Calcareous Cements,* 1847.)

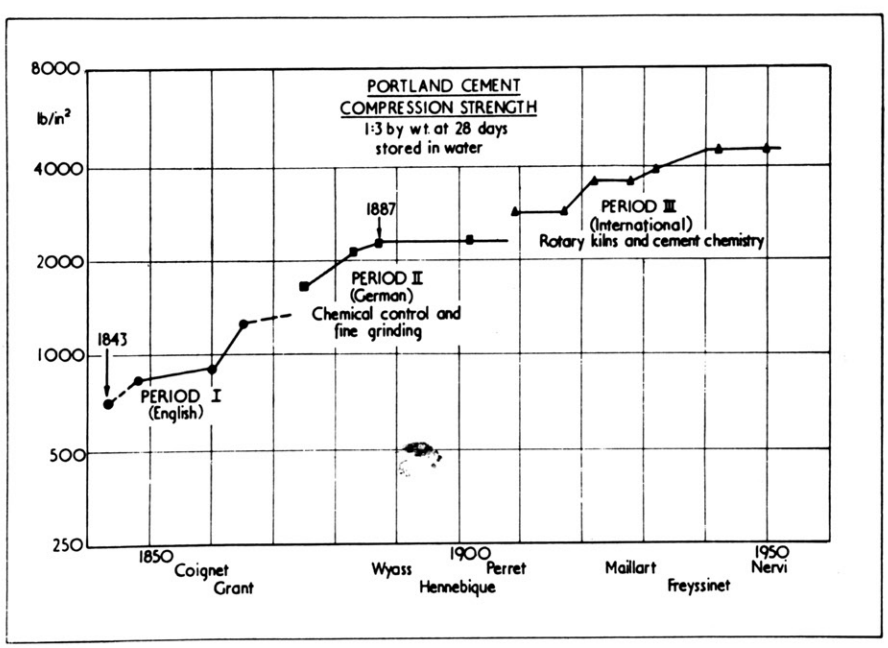
6.7 Cement's resistance to tension was long tested by equipment developed from that originated by a French engineer. A mixture of one part cement and three parts sand was molded (*N*) and placed in the machine (*G, G'*). Lead shot was poured into a bucket (*Z*) suspended from a system of levers that multiplied its weight by fifty. (*Science, Progrès Découvert,* 1 October 1932.)

6.8 Over the century from 1850 to 1950, the compressive strength of Portland cement increased by more than five times. A. W. Skempton has charted test results from this period, and with such evidence has identified three major periods of development. (*Transactions, Newcomen Society,* 1962–1963.)

time of a cement. A thick paste of water and the lime to be tested was placed in a container and covered with water, whereupon tests with a weighted, blunt knitting needle indicated when the sample had solidified. A weighted needle was dropped about two inches, and its penetration into the sample showed the relative hardness.[16] With similar concerns, General C. W. Pasley of the British Royal Corps of Engineers tested the adhesion of mortars made of different cements by attaching brick after brick to a wall, each beyond the other to form a cantilever (fig. 6.6). Each brick took only about six minutes to set up, and any cement that allowed 18 to 20 bricks to be added before they fell was considered acceptable for use, although the maximum performance was over 30 bricks.[17] This system of testing mortars is said to have been in common use from 1830 to 1850.

In preparation for construction of the new main drainage system for London, John Grant, chief engineer of the Metropolitan Board of Water Works, in 1858 began methodical testing of Portland cements. To determine tensile strength, small briquets of cement paste were molded in a figure eight shape (fig. 6.7). When inserted between two clips, the briquets would be pulled until they broke. To determine their compressive strength, molded blocks of cement were crushed in hydraulic presses. Grant's discoveries were immediately translated into specifications for the materials to be purchased for work on the drainage system. In 1859 a new requirement appeared in the specifications for the Southern High Level Sewer: "The whole of the cement to be used in these works and referred to in the specifications is to be Portland cement of the very best quality, ground extremely fine; weighing not less than 110 lbs. to the striked [leveled] bushel and capable of maintaining a breaking weight of 400 lbs. on an area of 1½ inches by 1½ inches equal to 2¼ square inches, seven days after being made in an iron mold . . . and immersed six of these days in water."[18] Grant believed strongly that the weight of cement related directly to its strength and for years specific gravity was a common requirement in specifications.

In much of the last half of the nineteenth century, advances in testing methods centered in Germany,



where the manufacture of Portland cement had begun in the 1850s (fig. 6.8). Improvements were largely the result of advances in kiln design that increased the uniformity of output and the introduction in 1871 of systematic chemical analysis of all the raw materials used. A greater proportion of lime and higher kiln temperatures resulted in a harder clinker. By 1875 it was recognized that the larger grains of ground clinker did little to strengthen cement, and within two years only 3 or 4 percent of the particles in the typical German cement were too large to pass through a sieve with about 6,000 holes in a square inch. All of these technical improvements were assisted by the German government, its testing laboratory, and the facilities of the country's technical universities.

The chamber kiln for manufacture of cement originated with a patent of Isaac Johnson in 1872, and it was used with the "wet process" in which powdered ingredients were mixed with water, dried, and then burned. To construct a chamber kiln, a rectangular chamber as long as 100 feet was built at the side of a usual bottle kiln (fig. 6.9). The top of the kiln was closed and a chimney was located at the other end of the horizontal chamber. In this chamber sufficient liquid slurry was poured to load the kiln when it was dried, and while one load was fired, its exhaust heat dried the slurry for the next firing. Later improvements stacked two or three chambers, decreasing the required length and increasing the kiln's efficiency. Two factors worked against continued use of the chamber kiln. First, a large amount of labor was required to fill the chambers with slurry, remove the dried powder, and load the kiln, and when the fluctuating price of coke rose the chamber kiln was no longer economically sound. Second, after the development of a wet-grinding process that used less water, a smaller area was needed for drying slurry.[19]

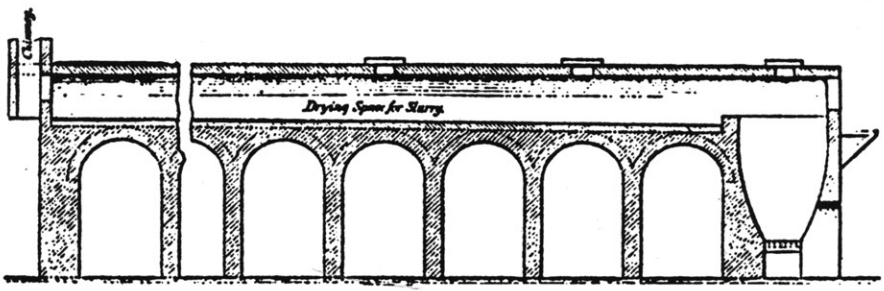
The shaft kiln was generally limited to the Continent, where dry grinding was more common. (The choice between "wet" and "dry" grinding processes was largely based on the materials to be used.) As in early bottle kilns, raw materials were entered at the top and clinkers fell to the bottom (fig. 6.10). Fans were developed to increase the draft, and mechanical grates prevented clogging. The shaft kiln was economical of labor and fuel, but it did not produce a uniform firing at a time when the control of quality was a primary factor in the competition among the many companies manufacturing cement.[20]

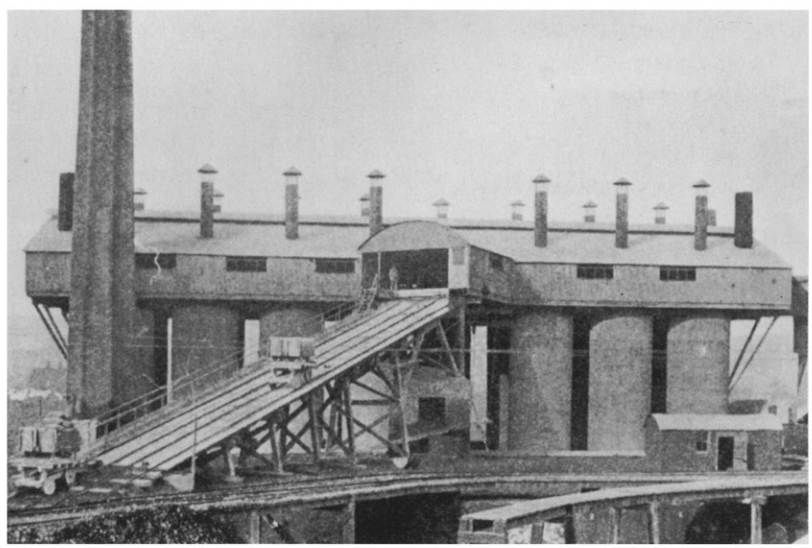
Before the rotary kiln, all designs had been based on the bottle kiln, the elementary means of burning the ingredients for cements. The best known rotary kiln was that designed in 1885 by Frederick Ransome, who had earlier obtained a patent for making "artificial stone." The first Ransome kiln consisted of an iron cylinder, 21 feet long and 3½ feet in diameter, mechanically rotated on rollers (fig. 6.11).[21] The cylinder was slightly tilted, powdered material being poured in at the upper end and gas flames situated at the lower end of the kiln. It was hoped that this arrangement would permit continuous operation with more reliable quality. A series of very costly tests were conducted at several English cement plants over a two-year period, and they all failed. As the powder was fired it melted, caked together, stuck to the firebrick lining of the kiln cylinder, and thus impeded the movement of material within the cylinder. Also, any effort to recirculate hot air in order to raise temperatures resulted in

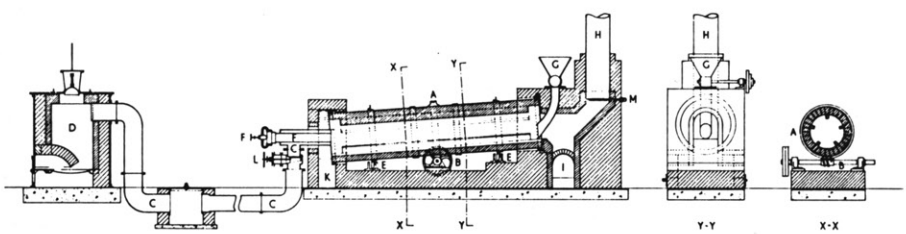
6.9 Isaac Charles Johnson patented his chamber kiln in 1872. While operating the cement works that had been vacated by the bankruptcy of Aspdin, Ord and Company, Johnson found a way to use the heat of a kiln to dry slurry. The upper and lower parts of the bottle kiln were moved apart as much as 100 feet, connected by a horizontal chamber in which slurry was poured about 8 inches deep. (A. J. Francis, *Cement Industry 1796–1914*, 1977.)

6.10 Shaft kilns of this sort were much like bottle kilns but continuous in operation. They were fed at the top with fuel and dry blocks of material, burning took place at mid-height, and the calcined material was taken out at the bottom of the shaft. (C. A. Davis, *A Hundred Years of Portland Cement*, 1924.)

6.11 Frederick Ransome built his rotary kilns at several English cement works. This one, built for the Arlesey Lime and Portland Cement Company, had a cylinder about 5 feet in diameter and 25 feet long. The rotary kiln worked well at lower temperatures, but, once the raw materials were burned to the degree required, the gummy substance adhered to the firebrick lining of the kiln. (*Proceedings, Third International Symposium on the Chemistry of Cement*, 1952.)







the fine powder clogging any passages through which the hot air flowed. While Ransome's tests and revisions continued, a young civil engineer, Frederick Stokes, in 1888 patented an improvement, using the regenerative principle of industrial furnaces. The Stokes rotary kiln included a burning cylinder 35 feet long, from which hot gas was exhausted into another cylinder, slightly longer, the outside of which was coated with a slurry of the powdered material.[22] The liquid mixture was dried, the chunks of material it produced then entered the burning cylinder, and from there clinkers traveled into a cooling cylinder.

Variations and improvements followed. The Continent led in finding the advantages of longer rotary kilns, and what had first been a length of 60 feet grew to as much as 250 feet by 1924. In the United States the development of longer rotary kilns was led by the Edison cement works, and by 1922 more than three-quarters of U.S. plants had rotary kilns longer than 100 feet.[23] The knotty problem of cylinder linings was unsolved by experiments with bricks of magnesium or bauxite. After some years, a method was found to line cylinders with ground clinker, to which the burned material would not adhere.

The first great route into the western reaches of the United States was the Cumberland road, and the second was the Erie Canal. Connecting Lake Erie and the Atlantic via the Hudson River, the canal sped the flow of settlers to the West and established New York as the principal port of the east coast. Construction of the canal was supervised by Judge Benjamin Wright, a lawyer previously responsible for engineering two small canal projects, and one of his assistants was a young surveyor, Canvass White. In 1817, after a year working with Judge Wright, White went to England at his own expense to spend several months tramping along more than 2,000 miles of canals. White interviewed engineers, obtained drawings of canal construction, and apparently probed all aspects of canal building.

Commissioners for the Erie Canal made no budget provision for the purchase of imported hydraulic cement, which had been strongly urged by Judge Wright, and stonework laid in common lime mortar in 1818 quickly showed signs of deterioration. When their suppliers of lime burned one local stone and delivered the lime made from it, it was discovered that the mortar did not crumble in water—usual with ordinary lime—and the supervising engineers were informed. Tests confirmed that when this stone was burned, powdered, and mixed with sand and water it would indeed harden, even when submerged in water. After he had investigated the material, Canvass White was granted a patent in 1820 for the first natural cement to be manufactured in the United States, a cement made from stone that had lime, silica, and alumina in proportions producing a hydraulic cement. White's patent was later bought by the state of New York, which resulted in the removal of all manufacturing restrictions related to the patent.[24] In the year that the Erie Canal was opened, White opened his cement works at the village of Chittenango, New York. Leaving his younger brother in charge of manufacturing "White's Water-Proof Cement," Canvass White went on to follow a career as an authority on the construction of canals.[25]

Hydraulic cement proved essential to the construction of other canals, and most such projects began by

establishing a quarry that could provide stone for manufacturing natural cement. The Delaware and Hudson Canal led to the opening of cement production in the Rosendale area of New York, where at the end of the nineteenth century 42 percent of the American natural cement was produced.[26] Such cement plants had the considerable economic advantage of a large and long-lasting initial market supplying the canal builders, and this start often provided them enough financial stability to allow expansion of their market areas after the canal had been completed.

In 1903 a critic of natural cement wrote gloomily in *The American Architect*:

> It is well known to cement-men that natural plants turn out a product that varies very perceptibly from day to day, . . . [as] the quality of rock in the same quarry frequently differs in its chemical constituents. . . . However, every pound of the variable "raw" material is subjected to the same treatment. . . . The method of calcination in a natural plant, after half a century of experience, is astonishingly crude; . . . nor is it certain that the ordinary vertical kiln now in use will *ever* produce a high-testing cement.[27]

The criticism was harsh, but its reasoning was irrefutable. Markets for natural cement had increased with the nation's growth. Even when no canals and few buildings were being built because of economic crises, the ceaseless westward expansion of railroads afforded a fair level of business. At the same time, the German cement industry had been rapidly advancing, while American manufacturers remained unwilling to learn more of Portland cement or to invest in a drastic improvement of their methods of production.

The construction of iron and steel ships had begun an upward climb around 1860, but in the decades remaining in the nineteenth century there were still many wooden ships afloat. Liners to carry tourists and valuable cargo might be built of metal, but more mundane goods were usually carried in wooden vessels, which were unable to flood their compartments with water as ballast. They came to America and loaded with agricultural products, particularly grains and cotton, for the trip to Europe. For the westward voyage the ships' masters were willing to take on heavy loads for little payment. The arrival date of such shipments was somewhat unpredictable, because the departure date and the cargo to be taken on were often known only at the last moment. On the other hand, there might be no charge for shipping barrels of cement to the United States. In fact, when highly profitable cargo was scheduled for the return trip, purchasers of cement could be paid as much as ten cents a barrel to hurry the unloading.

At first the dominant share of imports was English. Later the German makes became more popular because of their high quality, and Belgian brands were used because they were extremely low in price. Even with savings in transatlantic shipping, the price of imported cement might be as much as twice the price of good quality Rosendale cement from New York, and railroad rates were high for shipping cement into the Mississippi River valley, even during the periodic price wars among railway companies. In spite of the erratic scheduling of shipments from Europe, importers endeavored to receive much of their cement during the summer so that the barrels could be shipped westward on canals, which charged a lower rate at that time of the year.

American-made Portland cement was first marketed by the Coplay Cement Company in the Lehigh River

area of Pennsylvania. The company began producing natural cement in 1865, and six years later David O. Saylor, one of the owners, patented a method of making Portland cement. Several years of experimentation had convinced Saylor that his plant could be adapted for the necessary steps of manufacturing Portland cement: grinding the stone into a fine powder, adding lime when his stone required it, obtaining a clinker with high heat, and grinding the clinker into a fine powder. By 1876, "Anchor Brand," as Saylor's Portland cement was known, had won the highest award at the Centennial and had been specified by U.S. government engineers for use in jetties constructed by the engineer James B. Eads in the Mississippi River's delta area. There were also large sales of "Improved Anchor" cement, in which the company's clinkers for Portland cement were mixed with the stone for its natural cement.[28]

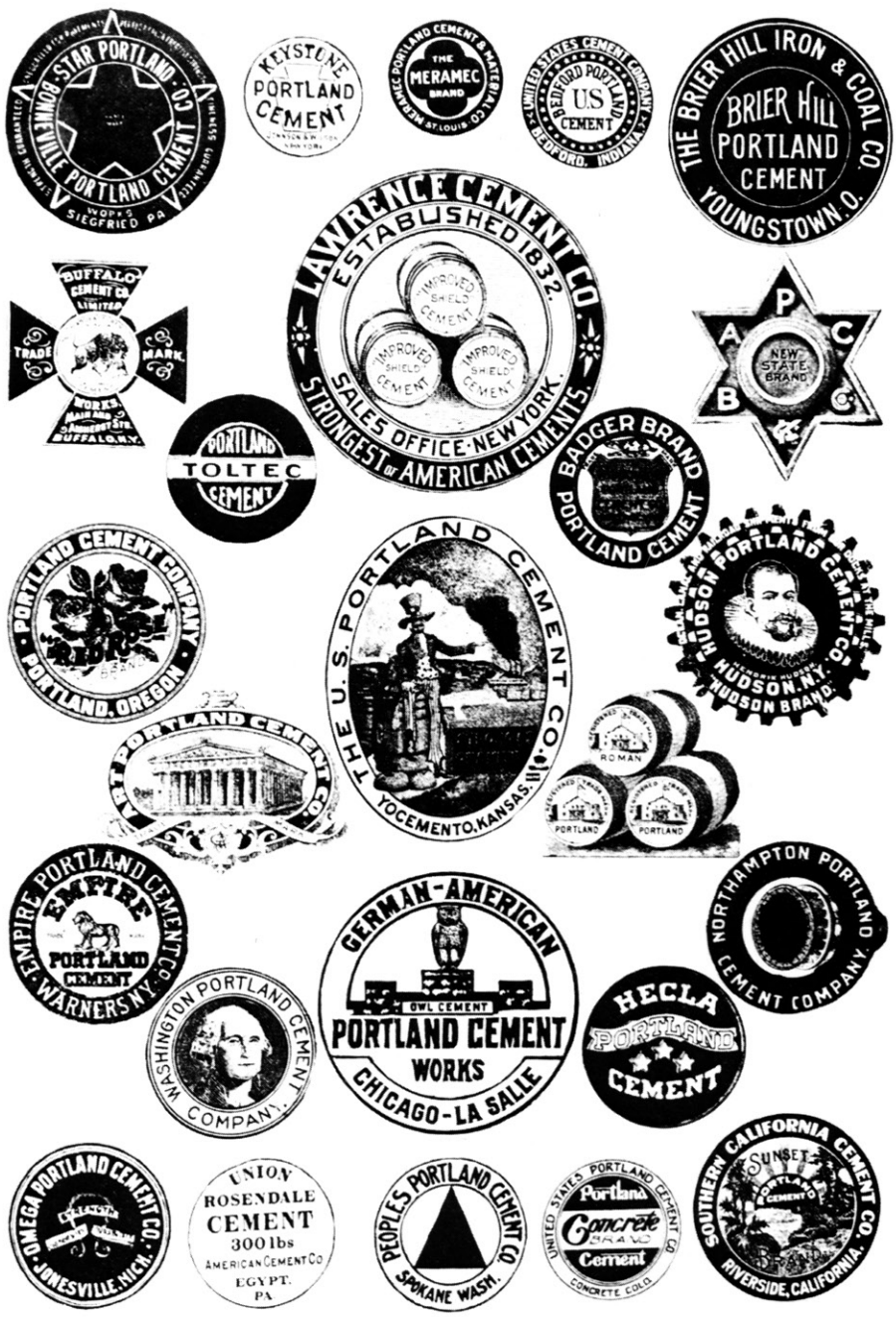
6.12 When cement was shipped in wooden barrels, manufacturers in the U.S. and some other countries marked their product by stenciling trademarks on the barrelheads. Stenciling cloth bags was more difficult and, when bags began to replace barrels for shipping, printed paper labels became more popular as a means of marking both bags and barrels. (Concrete, April 1923.)

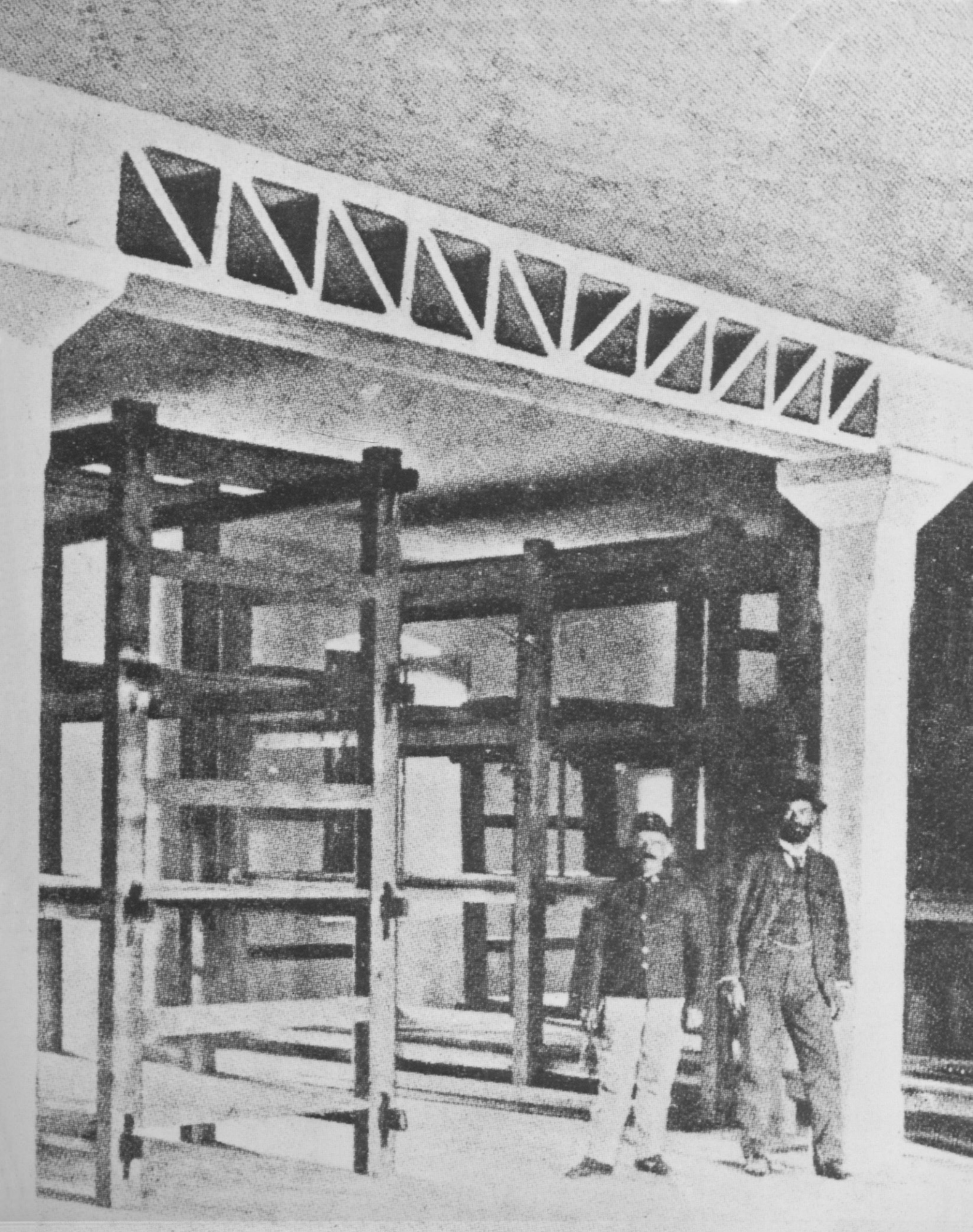
An American design for a rotary kiln to make Portland cement was installed in 1886 by José de Navarro, a New York entrepreneur and owner of the Union Cement Company. After two years of trials the kiln proved unsatisfactory and a Ransome kiln was substituted when the company moved to the Lehigh Valley in 1888.

By the 1890s many cement plants had begun shifting to the production of slag cement, which had originated in Germany almost 30 years earlier. In the United States slag cement, which was officially classified as a "puzzolan" cement, resulted from finely grinding the waste of blast furnaces and mixing it with powdered lime. It was commonly sold under the name "Steel Portland Cement," but a government board insisted that it should not be classed as a Portland cement. In response to this, steel companies, which had understandably become enthusiastic investors in cement making, started experiments to improve slag cement. They found that by grinding both slag and limestone, the clinker resulting from the mixture made a true Portland cement. By 1912 cement made of this mixture was about 13 percent of the total U.S. production of Portland cement, but sales began to drop after that time.[29]

By the end of the nineteenth century, production of natural cement had virtually ceased in Europe. In the United States, however, Portland cement was only 28 percent of domestic production in 1896, and the amount of Portland cement made in the United States was half that imported.[30] At that time, about two-thirds of the U.S. production of Portland cement came from the Lehigh Valley of Pennsylvania. By 1923, over 90 times as much Portland cement was manufactured, but only a quarter of it came from the Lehigh Valley.[31] The cement industry had scattered, with a growing production from plants west of the Mississippi River.

Just as ingredients are added to produce a Portland cement of the desired quality, other additives may be used to obtain desired results. It was discovered early that the addition of gypsum retarded the setting of concrete, which is sometimes useful in construction. Other additives can accelerate the rate at which concrete gains strength with time. Since the action of cement as concrete hardens is extremely complex, the chemical determination of cement characteristics has become a focus of attention.





Technics and Architecture

The Development of Materials and Systems for Building

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1836 Uses of concrete described in George Godwin's paper at the Royal Institute of British Architects

1854 System for reinforced concrete patented (Britain) by W. B. Wilkinson

1867 Joseph Monier patents (France) his system of reinforced concrete, exhibits at the Paris Exposition

1873–76 Construction of the Ward House, Port Chester, New York

1875 Residential construction with concrete panels patented (Britain) by W. H. Lascelles

1877 Thaddeus Hyatt publishes *An Account of Some Experiments with Portland Cement Concrete*

Monier patents (France) a method of reinforcing concrete beams

1884 Ernest L. Ransome patents (U.S.) the twisted square bar as the basis of his system

1892 Patents of François Hennebique give rise to an international enterprise

1900s Flat slab construction developed by C. A. P. Turner and Robert Maillart

Introduction of construction using precast structural elements

German, French, and British regulations published for design of reinforced concrete structures

1903 Ingalls Building, Cincinatti, Ohio, the first skyscraper of reinforced concrete

Auguste Perret's apartment building at 25b Rue Franklin, Paris

1903–06 Housing built in Liverpool using John Brodie's system of precast panels

1910s "Unit systems" of precast concrete construction introduced by Ernest L. Ransome and John E. Conzelman

1918 Duff Abrams publishes results of his tests on the water-cement ratio in concrete

1922 Z-D thin-shell dome constructed in Germany for use as a planetarium

7.1 A drawing published in 1859 shows concrete, a mixture dry enough to be carried in a basket, being tamped in wooden formwork. (*Über Land und Meer*, 19 January 1859.)

Concrete was used in constructing the walls around a fourth-century B.C. Roman city some forty miles east of Rome, and by the second century B.C. the new material began to be used for buildings in Rome.[1] In constructing walls, Roman concrete was in some respects merely mortar, for bricks were laid for the faces of walls and mortar was poured between over chunks of stone and broken brick. But in vaulting, which became the dominant theme of Roman architecture, concrete was clearly used according to its own nature, that of a plastic material to be molded until it developed sufficient strength to stand alone. Once the masonry walls reached the required height, wooden formwork for vaulting was set in place. The scarcity of wood in much of the Roman empire demanded economy and ingenuity in preparing formwork. In some cases it is believed that a portion of a long vault would be built, and the forms lowered and moved on to construct the next part of the vault. Certainly, in all cases it was desirable that formwork be reused as much as possible. Alternate floors of multistory buildings were often supported by concrete vaults while the floors between would be framed with wood beams.[2] Planks that shaped the soffit of a vault sometimes were covered with one or two layers of flat square tile, but it is debated whether these tiles had the function of giving additional strength to the forms or simply provided a surface for plastering the underside of the vault once the wooden formwork had been removed.[3] It was the technique of concrete construction that constituted the basis of the spatial order found in Roman architecture.

Medieval architects relied on stone in most construction. For foundations, Gothic builders usually filled a trench with stone rubble and tamped it hard to serve as a level for the first course of masonry, but for "some important buildings, a better foundation was made with strong concrete of rubble and lime-mortar."[4] Entire walls might be made of rubble, to be plastered over, but often the outside surfaces were of carefully fitted ashlar, with mortar and small stones used to fill the inside of the wall.

Much of the early study of cement was directed at the improvement of mortar, particularly that used in the massive harbor works built for the eighteenth century's active maritime trade. Nevertheless, cement was recognized as having advantages when used as concrete. The French architect Philibert Delorme wrote in 1536:

> The excavations being made, whether for houses, harbors, bridges, or buildings in a marshy soil or even on land, and if, being deep and wide, stones of a large size cannot be used for the foundations, the best and surest method is to prepare a mortar composed of quicklime recently burnt, mixed with river sand which contains a quantity of pebbles of all sizes. . . . The composition thus executed hardens and solidifies so firmly in the foundations that, being heaped up in a mass and bound together, it becomes a uniform body or rock, such as nature forms, of a single block and so strong and hard that when dry it cannot be broken either by piles or any other instrument, nor can the pebbles be separated from it without breaking them to pieces.[5]

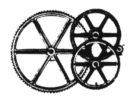
A variety of methods were used. According to George Godwin's essay on concrete, which won the medal of the Royal Institute of British Architects in 1836, for foundations a mixture of lime, water, and stone might be placed in a trench, layers of stone could be compacted with layers of grout poured over them, or the lime and stone could be thrown dry into a water-filled excavation.[6] Debates about critical innovations in the development of concrete were as common

then as now, because instead of its being a new material it was developed gradually from the traditional methods of using grout in masonry. In fact, it was the late 1830s before the term "concrete" replaced "grouting" as the accepted reference to solid masses in which cement, sand, water, and stones were combined.[7]

Sir Robert Smirke, a Greek Revival architect best known for his design of the British Museum, exerted a strong influence on the popularization of concrete. It was Smirke's recognized skill in construction that led to his being asked to correct the faulty foundations of Millbank Penitentiary. The building had started as a project of Jeremy Bentham, the social reformer who had written on prison improvements, but a succession of architects of diminishing ability had tried to cope with the marshy site, in which foundations began to sink almost as soon as they were completed. In a complex operation, Smirke underlaid the penitentiary with a layer of large stone and gravel, pouring a thick covering of concrete over it.

Sixteen years later, when Smirke's British Museum was under construction, he followed his customary method for using concrete in new construction. Under load-bearing walls the concrete foundation's vertical dimension was 2½ feet, and the Museum's magnificent colonnade rested on concrete 6 feet thick.[8] The practice of the time was to make certain that each wheelbarrow of concrete was thrown into the excavation from a height well above the foundation. Smirke insisted on a height of at least 6 feet, and a specification cited by Godwin required a height not less than 9 feet.

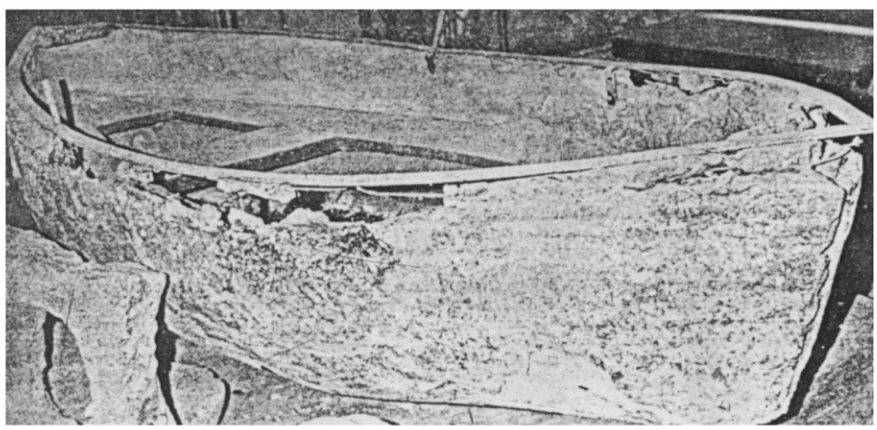
At the Paris Exposition of 1855 there was exhibited a boat made six or seven years before of concrete (or cement mortar in present-day terms) and wire reinforcement by a Provençal landowner, Jean-Louis Lambot (fig. 7.2). The boat was almost 12 feet long and over 4 feet wide with sides around 1½ inches thick.[9] Soon after the Exposition, Lambot took out patents in France and Belgium, but his *ferciment* attracted little attention. In 1844 a Bristol physician named Henry Fox obtained an English patent for a floor system in which wood laths were fastened on the bottoms of cast-iron joists and the plaster troweled on them acted as a base for filling concrete between and above the joists.[10] Neither of these systems constituted reinforced concrete in which the compressive strength of concrete and the tensile qualities of metal worked together. Lambot's boat seems to have used wire to avoid the problems that would arise from cracks, and Fox's floors used concrete as a mass that spanned between the iron joists.



The essential nature of the combination of iron and concrete was understood by a plasterer, William Boutland Wilkinson, who manufactured plaster of paris and Roman cement in Newcastle upon Tyne.[11] In his 1854 patent Wilkinson described a shallow-arched floor slab in which iron strips cut as for barrel hoops would be set on edge at the crown of the arches "so that in this low position the strips may act with more power as tension rods." An alternative form of reinforcement was wire cable, which could easily be bought second-hand from mines. Patent drawings show the cable draped so that it was at the bottom of the slab at mid-span and at the top over supports, clear indication of an intuitive or reasoned understanding of the structural action required of a tensile material.

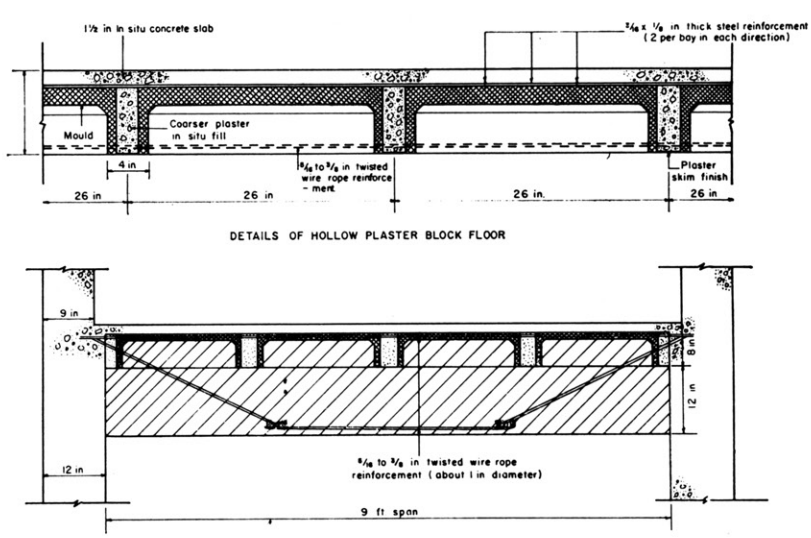
7.2 The remains of one of Jean-Louis Lambot's boats, as exhibited in a local museum. In 1955 a dry summer caused the water level in the lake on the Lambot estate to drop, and two concrete boats appeared in the mud, over a century after they had been fashioned out of *ferciment*. (*Concrete*, November 1967.)

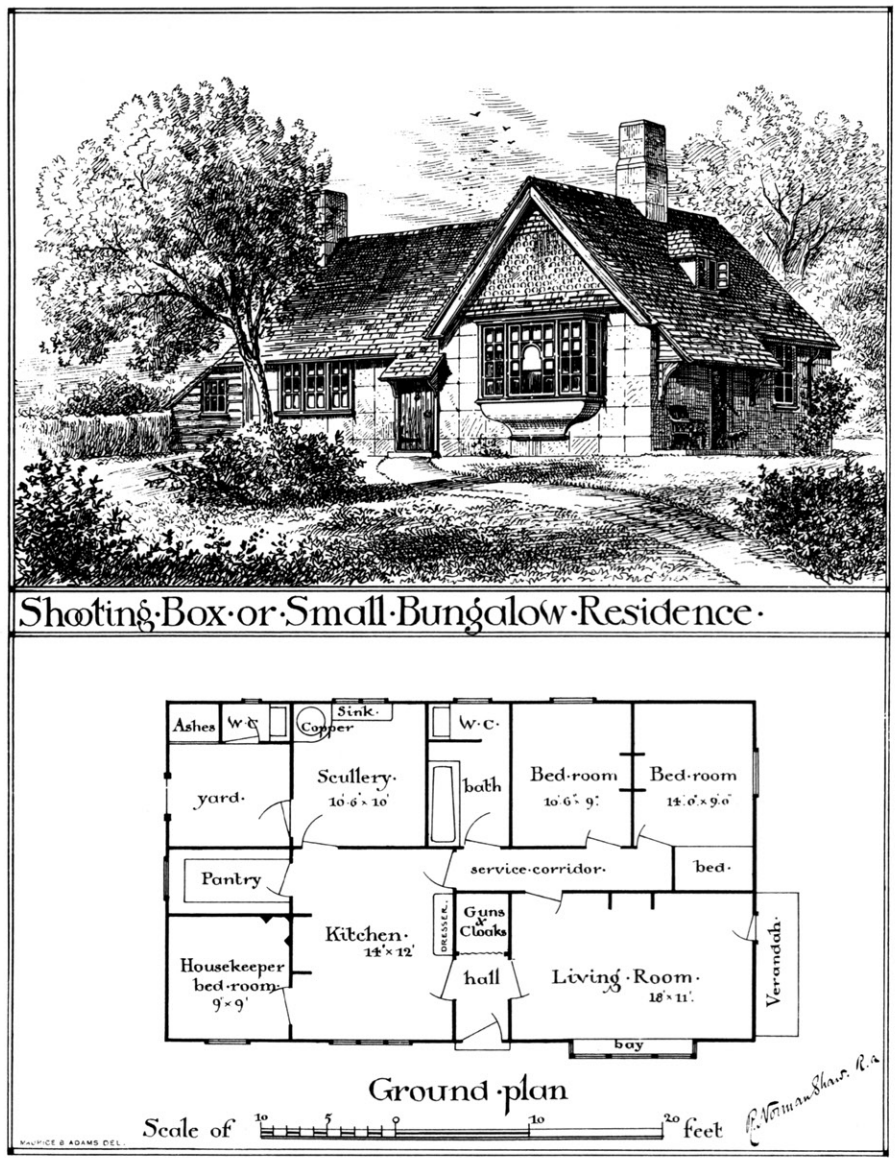
7.3 A modern drawing of a Wilkinson floor system, built about 11 years after his patent, shows the square plaster forms and the very narrow beams between them. The upper drawing shows the center portion of a floor, and the lower drawing shows a supporting beam that spanned 9 feet. (*Structural Concrete*, July–August 1965.)



Even more indicative of Wilkinson's knowledge was the evidence discovered in 1954 in a residence he had built at his plasterworks around 1865. A careful inspection before the building was demolished showed that the floor of the upper story had been made by placing plaster molds upside down on formwork (fig. 7.3). The molds were about 22 inches square, and concrete was poured into the gaps between them to form a grid of beams. Concrete over the molds formed the floor.[12] Reinforcement for these small beams was wire cable, located at the bottom of the concrete but sloping upward at the ends. The slab that resulted spanned about 12 feet in each direction, and a grid of steel rods was placed at the bottom of the 1½-inch floor slab that covered the molds. In a larger beam the wire rope again rested at the bottom in the center of the span and sloped upward toward the ends.[13] The complementary actions of concrete and reinforcement had obviously been understood.

A different potential of concrete was explored when a patent for an "Improved Method of the Construction of Buildings" was taken out in 1875 by William Henry Lascelles, a general contractor in London. Before having his own construction company, Lascelles had worked with concrete in the construction of workers' housing for the Improved Industrial Dwelling Company, a philanthropic organiza-





7.4 This two-bedroom cottage is one of the designs using Lascelles's system that were published by Richard Norman Shaw in 1878. The concrete panels are evident on the exterior, but they have no definite relationship to the location of interior partitions. (R. N. Shaw, *Sketches for Cottages and Other Buildings*, 1878.)

tion.[14] Lascelles's system was intended to be used in constructing inexpensive houses (fig. 7.4). A wood frame was erected, and on both sides of the studs and braces concrete panels, 2 feet by 3 feet and 1½ inches thick, were fastened with screws. The panels had simple butt joints at their vertical connections, which fell in the centers of the framing members, and Lascelles claimed that the walls admitted no water.[15] The joints of roof panels were filled with cement and covered with tiles. Lascelles experimented with concrete joists and rafters, but they proved to be much more expensive than wood. Many of the panels for exterior and interior walls and ceilings were molded in the patterns of traditional wood paneling; others for roofs and exterior walls bore a fish-scale pattern in imitation of roof tiles. The panels were reinforced by two half-inch-diameter iron rods placed diagonally, and floor panels had reinforcement of wire mesh.[16]

At the time that Lascelles patented his system for building low-cost cottages of concrete, he was acting as general contractor on projects under the supervision of Richard Norman Shaw, an architect particularly known for his tasteful and imaginative designs for residences. Around 1875

Shaw built a convent, for which the low budget encouraged use of concrete walls in much of the building, although portions of the concrete were covered with roof tiles. At the same time Lascelles was acting as contractor for a residence and studio that Shaw had designed for a popular genre painter, Marcus Stone. In Stone's house, molded concrete was used for the frames of three large windows that admitted light to the painter's studio on the top floor. The thin concrete frames, reinforced with a single rod in each mullion, permitted a lightness equal to that of wood, which the Building Act of 1774 had virtually prohibited on the face of buildings.

Although Lascelles built only a few of Shaw's projects between 1875 and 1878, there seems to have been a degree of collaboration in the development of Lascelles's patent. Two model cottages designed by Shaw were constructed on the grounds of the Paris Exhibition of 1878, and inside them Shaw's drawings of other designs using the patented system were displayed. At the same time in England a small booklet was published, *Sketches for cottages and other buildings: designed to be constructed in the patent cement slab system of W. H. Lascelles, . . . From sketches and notes by R. Norman Shaw.* The cottages were not among the best of Shaw's work. If they exhibited any of Shaw's principles, either in drawings or in those that were built, it was chiefly in their picturesque qualities and their color. Exterior panels were tinted by mixing the concrete with Spanish red, an iron oxide pigment that produced a color the public thought alarmingly vivid until time and soot had mellowed it to a rich terra-cotta tone. While the early hue shocked lay people and professionals alike, to Shaw any color was preferable to the pallid hues of classical architecture, and pigments that could provide lasting color in concrete were extremely rare. One significant change was made in Lascelles's system: concrete studs replaced the wood framing described in his 1876 presentation to the Royal Institute of British Architects, and metal members encased in concrete served as joists.

In the 1870s the most complete knowledge of the structural fundamentals of reinforced concrete seems to lie in the studies of Thaddeus Hyatt, a manufacturer of sidewalk gratings made of metal and glass that were employed to light basements.[17] Hyatt had begun manufacturing his "vault covers" in New York sometime during the 1840s. The business was well established by 1856, when Hyatt became active in support of the abolitionist settlers in Kansas. After he spent thirteen weeks in a Washington jail for his refusal to testify in Congress's investigation of the Harpers Ferry incident, the new Lincoln administration assigned him as American consul in the French port of La Rochelle, where he remained from 1861 to 1865. It seems safe to assume that Hyatt's curiosity would have led him to learn more of French experiments in concrete construction. When he left his consular post and returned to business, Hyatt immediately started experimenting in London with new ways of building sidewalk panels, and this led him to the study of concrete.[18]

Hyatt published his findings in 1877 as *An Account of Some Experiments with Portland Cement Concrete Combined with Iron as a Building Material.* All of Hyatt's tests, whether made by himself or in testing laboratories, are summarized to present the essentials on which the use of reinforced concrete is based today. He stated that the strength of iron does not withstand fire, and showed that all iron reinforcement should be completely sur-

7.5 It took four years to build W. E. Ward's concrete house in Port Chester, New York. Much of this time was due to caution. One year after a floor had been laid, Ward loaded it with 26 tons and left the load there through the winter. (*Transactions, American Society of Mechanical Engineers*, 1883.)

rounded with concrete, which resists fire. After a blazing fire had been kept under a concrete slab for ten hours, cold water was sprayed on the underside of the slab. No damage was detected, even after the slab had undergone a second heating and cooling.[19] Hyatt also discovered that the bond between iron and concrete was sufficiently strong to make reinforcement in the bottom of a beam act in conjunction with the concrete in the top, a fact that made a network of rods or straps more effective than the older method of embedding I-beams in concrete. Of the tests made on more than 50 beams by David Kirkaldy's laboratory, Hyatt wrote:

> A study of these [test results] will show, from the breaking of the metal, first, that all of the blades of iron were perfectly held while the beam was under strain; secondly, that the two materials worked in perfect harmony; and thirdly, that the proportionate power of the metal increased regularly as it became tie-metal . . . the higher the blades the more they lost as *tie*, and the more they gained as *compressive* material, the portion which came into compression being so much metal relatively lost, inasmuch as there was concrete enough to do this part of the work without it.[20]

Learning that the two materials expanded and contracted at almost the same rate under heat, Hyatt established the durability of the combination when subjected to fire or cold. For concrete columns Hyatt proposed a combination of longitudinal reinforcement and hoops. Furthermore, he patented precast planks of concrete that have a striking resemblance to many used today.

While Hyatt's reinforcement was straps of wrought iron placed on edge, he was aware that they would have been more efficient if placed flat and explained that he used them on edge only because the work was done more quickly that way. Iron straps afforded a larger surface area for bonding with the concrete than did round or square rods, and Hyatt favored the use of straps that had ridges on their surfaces to increase this bond.[21]

In the words of E. L. Ransome, the systematic and highly analytical investigations of Thaddeus Hyatt "ended the 'period of discovery' and put the theory of reinforced concrete construction on a rational basis."[22] Unfortunately, Hyatt's costly tests drew no investors and patent infringements eliminated his opportunities to profit from his discoveries.

A more profitable venture was that of a young French gardener, Joseph Monier, who began in 1849 to make tubs and pots of concrete. Finding the tubs brittle, he embedded in them a mesh of iron. Roughly contemporary with Lambot's boat, the plant containers built by Monier utilized very similar methods to combat an outward pressure, the opposite of pressures on a boat's hull. By 1867 Monier had advanced his method to the point of obtaining a patent and exhibiting his work at the Paris Exposition of that year. His first extension of the patent's function seems to have been a water tank constructed in 1872 to hold over 30,000 gallons.[23] Tanks built according to the Monier system were usually constructed by erecting a cylindrical cage of vertical and horizontal rods and attaching formwork on either the inside or outside of the rods. Concrete was then troweled on the reinforcing to attain the desired structural thickness.

Monier obtained a patent for the reinforcement of beams, a patent "backed up neither by theory nor by systematic experiment."[24] As a struc-

tural principle it did not greatly differ from the French floor systems that had been in common use for several decades. As an American engineer commented in 1900, "The Monier patent is so broad, embracing in a general way any iron parts enveloped by cement, that it is difficult to understand why all the other systems are not infringements."[25]

Little was done with Monier's patents until the German rights were purchased in 1884 and sold the following year to G. A. Wayss, a civil engineer and contractor.[26] Wayss quickly instituted thorough experimental studies, employing the services of a government engineer, Matthias Koenen. In 1886 the first fundamental analysis of reinforced concrete's structural action was published by Koenen in a German journal of construction management. The next year he collaborated with Wayss on a pamphlet, *Das System Monier*, that became the first German handbook of concrete fundamentals.[27] It is believed that the French gardener's contributions to the development of reinforced concrete were basically intuitive. In fact, the story has been told that when he was shown concrete with reinforcement placed at the bottom, Monier disagreed with Wayss about that placement of rods and closed the ensuing argument by asking, "Who is the inventor, you or I?"[28]

In 1873, William E. Ward, a mechanical engineer who had been a founder of the Russell, Burdsall and Ward Bolt and Screw Company, decided to build himself a house in Port Chester, New York, on a hill overlooking the river and the factory of which he was manager. Ward engaged the services of Robert Mook, a New York architect, but few have flattered the style of the building, Second Empire forms with two towers, crenellated and machicolated.[29] There is little wonder that in Port Chester the house was called "Ward's Castle."[30] In its structure, however, the building was revolutionary (fig. 7.5). The entire house is of concrete, except for doors and windows, and the concrete was moistened with only enough water to result in adhesion of the materials and permit its being tamped in the formwork. Floors were made of concrete with small reinforcing rods and I-beams embedded in it. Their construction followed the method used by Ward in preparing an experimental beam, 5 inches wide and 12 inches deep. First, a 1-inch layer of concrete was tamped in the bottom of wooden formwork and, after an iron beam 4 inches high had been placed on the

7.6 In 1901 Ernest L. Ransome constructed this four-story machine shop for a manufacturer in Greensburg, Pennsylvania. Floors and columns were molded in turn, leaving expanses of window to light the factory's work areas. (E. L. Ransome and A. Saurbrey, *Reinforced Concrete Buildings*, 1912.)

7.7 The first step toward Ernest L. Ransome's Unit System was his U.S. Patent no. 694,580. As each floor slab was poured, extensions above and below completed the wall, except for the insertion of windows.

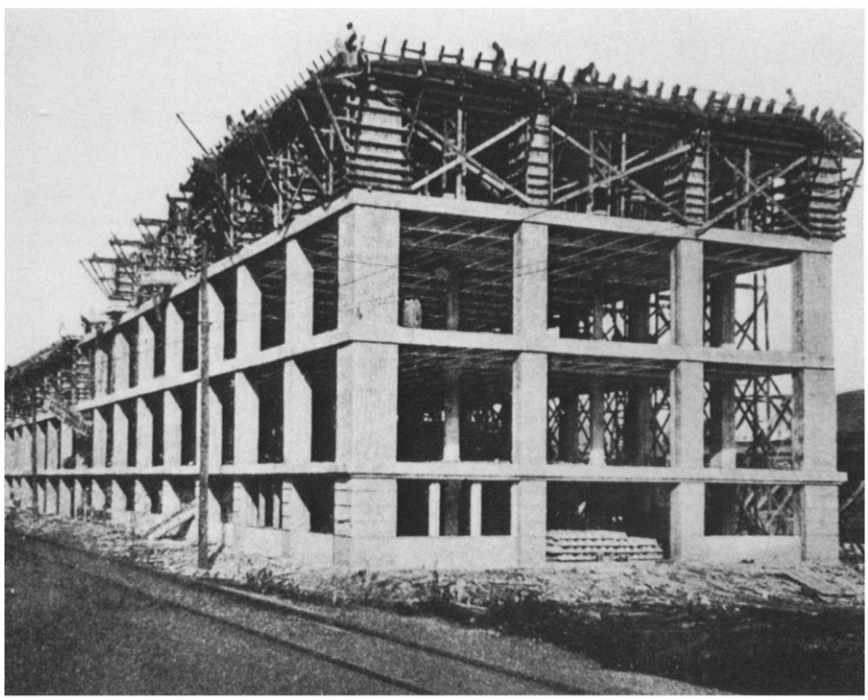
concrete, more concrete was filled around the beam and to the top of the formwork, 7 inches above the top of the iron. About eight years later Ward explained: "The reason for placing the iron beam so near the bottom of the mold was to utilize its tensile quality for resisting the strain below the neutral axis when this composite beam was exposed to heavy loads, while the *béton* above this line was relied on for resisting compression from load strain."[31] The concrete beams varied in span and size, and above them the floor slab was formed with 1 inch of concrete beneath iron rods (5/16 of an inch in diameter, spaced 8 inches apart in each direction) and with 2 more inches of concrete above the rods.

An exterior finish was provided by painting the walls with a mixture of cement and sand before rubbing the surfaces with abrasive stones. Plaster was applied on inside wall surfaces. One of the building's towers contained two concrete tanks, one for rain water and the other filled with water pumped from a spring. Porch columns were hollow and carried off water from the roof. Experiments made by Ward showed that it was possible to build lightweight interior walls of thin panels, two thicknesses of 2½ inches of concrete being cast with 6 to 10 inches of space left between them. Every 2 or 3 feet connectors between the surfaces unified the wall, and the space between was utilized to provide an ingenious radiant heating system. From a heater in the basement hot air rose within interior partitions, moved through channels in the floors, and returned to the basement through the outside walls. It was the gravity warm air system of that period converted to provide radiant heat. Although delay is always a problem of radiant heating, Ward reported that it took only five hours to bring all spaces of the house to 68° F when temperatures outside were about 30° F.

While the major American contribution to the theoretical development of reinforced concrete was made by Hyatt's experiments, mostly executed in London, the major practical advancement in the United States was the work of Ernest L. Ransome, son of the English inventor of a rotary kiln for firing cement. Ransome came to the United States to promote Portland cement manufactured by his father's firm, and soon he found his way to San Francisco, where in 1870 he became superintendent of the Pacific Stone Company. The principal uses of concrete at that time were foundations and the floor arches poured between I-beams. Ransome replaced the I-beams by placing a rod at the bottom of the concrete, therewith making concrete beams between the floor arches. This change effected considerable savings, but the cost of rods was doubled by the need to thread the ends of round rods and attach nuts in order to tie them firmly in the concrete. A less expensive method, which Ransome said was discovered while he twisted a rubber band, required twisting the entire length of square rods. Improvising a machine for this purpose, Ransome found that he could inexpensively twist bars up to 2 inches thick.[32] This formed the basis of his 1884 patent, and it was the cornerstone of the Ransome system of reinforced concrete construction.

By 1888 Ransome had moved from the construction of what he called "small and unimportant structures" to entire buildings of considerable size. There were claims that by twisting bars he weakened the metal in them, and many doubted the strength of his concrete floors. A test and demonstration was carried out during construction of a building for the California

Academy of Sciences: "To satisfy all skeptics in regard to the strength, a section of the second floor 15′ × 22′ was uniformly loaded with gravel to 415 lbs. per square foot; the deflection was ⅛″. For the further satisfaction of



the doubtful, the load was left on for four weeks, but very few availed themselves of invitations to examine the work a second time."[33] An addition to a borax plant at Alameda, California, marked Ransome's first use of ribbed floor construction, in which an arched underside of the floor slab was replaced by T-beams. This system, which had been used three years earlier in construction of an Amsterdam library, freed concrete construction from the traditions of iron beams and plaster arches.

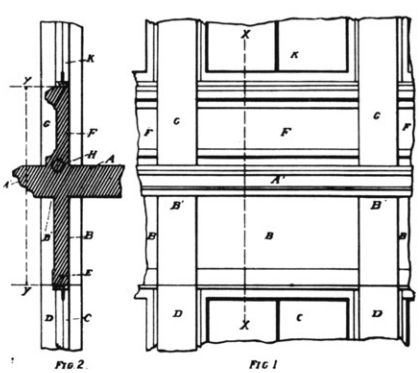


FIG. 2.

FIG. 1

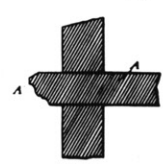
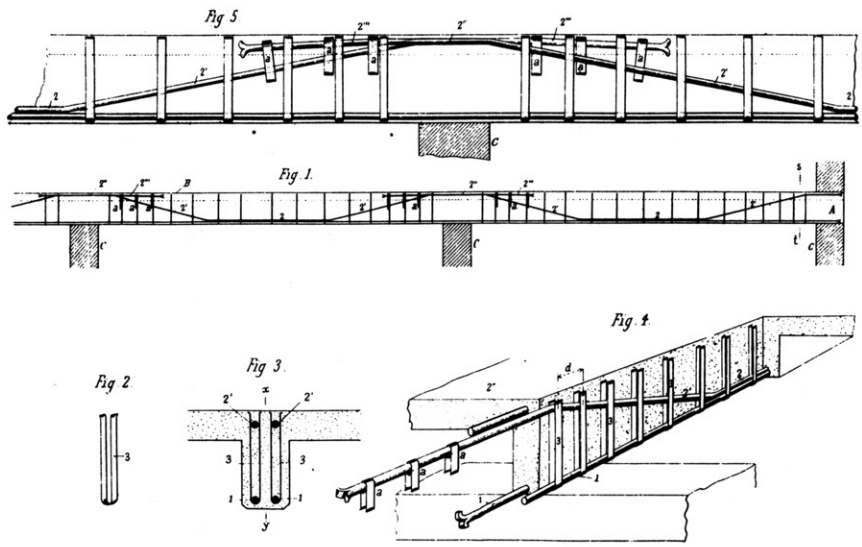


FIG. 3.

Through much of the 1890s Ransome spent his time promoting the Ransome system in competition with the other concrete systems then marketed in the United States, most of them distinguished from the others by a particular shape of reinforcement.



7.8 François Hennebique's patent "Improvements in the Construction of Joists, Girders and the Like of Cement." The vertical straps that serve as stirrups are correctly spaced more closely near the ends of spans. (British Patent no. 30,143.)

Moving his field of activity to the eastern states, he and his staff specialized in the construction of industrial buildings. In 1902 he patented a system in which his T-beam floors were combined with columns to form the concrete frame that was destined to dominate construction of factories and warehouse buildings (fig. 7.6). With the Kelly and Jones machine shop in Greensburg, Pennsylvania, Ransome ceased to treat concrete walls as substitutes for load-bearing masonry construction, and light curtain walls or broad expanses of windows were used to fill the bays of the concrete framework (fig. 7.7). Ransome's role was that of consulting engineer and licensor of others to use the Ransome system, which was principally characterized by the use of twisted square reinforcing bars.

Leadership in commercial development of reinforced concrete construction was first assumed by the German firm of Wayss and Freytag, which had bought and advanced the Monier system. Their system dominated Germany and Austria, and at first they also completed a surprising number of projects in France. Subsequently the organization of François Hennebique, begun eight years after Wayss and Freytag obtained the Monier patents, rapidly advanced use of the new material. Hennebique had apprenticed as a stonemason, and by 1867 he had established himself as a contractor with special capability and interest in the restoration of churches. His first reinforced concrete structure was a house in Belgium, for which Hennebique had planned to use Henry Fox's system that filled concrete between and over iron beams. While the plans were in preparation, a house of that construction burned near the site intended for the building, and Hennebique's client became justifiably determined that his house should not be prey to fire damage. Hennebique's solution was to dispense with iron

beams and replace them with steel rods near the bottom of the slab, but covered with enough concrete to prevent their being weakened by intense heat.[34]

In 1892, when he was 50 years old, Hennebique took out patents that covered more than a decade of his experimentation, and he forthwith closed his contracting business. An enviable organization was quickly put in place. Establishing his office in the role of professional consultant, Hennebique chose only the most reliable contractors as licensees. By building a technical staff and appointing agents in different parts of the world, he developed a marketing organization that permitted rapid expansion at the same time that close control could be maintained to assure quality. In its first seven years the Hennebique organization carried out over 3,000 projects, and it averaged about 100 bridges per year. Starting in 1892 with a single office and two engineer-draftsmen, five years later Hennebique had 17 offices, 56 engineer-draftsmen, and 55 licensees. By 1909 he had 62 offices, 43 of them in Europe, 12 in the United States, and the remainder in Africa and Asia.[35] A large part of the company's success may have been due to the remarkably advanced business techniques with which Hennebique operated his far-flung enterprise. Its magazine *Le Béton Armé* appeared monthly with informative articles for the Hennebique staff, as well as reports that advertised the company's accomplishments. Engineers joining the firm underwent a training program. Banquets celebrated every thousandth contract fulfilled, and the company slogan *Plus d'Incendies Désastreux* was boldly stamped on every drawing that the company issued or approved. One of Hennebique's most effective advertisements was the firm's offices built in Paris on Rue Danton (1898), a stone-looking building in which the thinness of concrete construction had made it possible to gain an additional story within the city regulations on height and some 90 square feet of floor area at every level.[36]

The fundamentals of Hennebique concrete design were incorporated in his patent for the reinforcement of beams (fig. 7.8). Bars were set near the bottom of the concrete, some extending the full length of the beam and others bent to the top as they neared the supports at the ends of the beam. These two sorts of bars were fastened together by slender U-shapes of strap iron (stirrups, as they are now called), which counteracted horizontal shearing forces toward the beam's ends, and the bars at the top of the beam resisted tension there when the beam extended across supports. This patent summarized the soundest discoveries that had been made in the previous two decades, and there are many who have attributed to Hennebique more eclectic and selective ability than inventive or theoretical insight. However, as the organizer of a corporation that could furnish professional services and extend the use of a new material, Hennebique had no significant competitors.

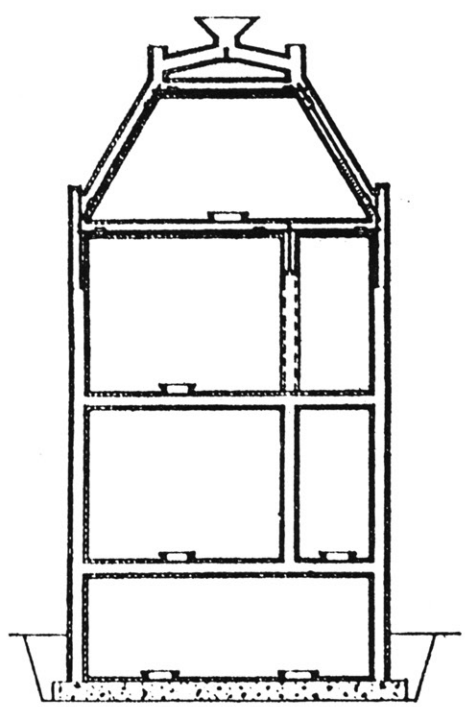
As there was inevitable competition among the commercial proponents of different systems of reinforced concrete construction, particularly those spawned by early activity in France, there frequently were concomitant battles over patent rights. Around the turn of the century Simon Boussiron and Paul Piketty built some structures in Paris that used methods resembling those introduced by Hennebique. Thereupon Hennebique sued, charging infringement of his patent of 1892 and the supplement he had filed the following year, which had introduced stirrups. The defendants replied with

an overall challenge to the validity of Hennebique's patent. They pointed out that in an 1878 addition to his basic patent, Monier had described his system of reinforcing beams, and the drawing submitted had shown some rods bent in a U-shape and placed upright. Although Hennebique claimed his patent offered the advantage of anchoring longitudinal rods to the stirrups, the patent court was unmoved. Its decision stated that the patent of Buissiron was invalid because it was not sufficiently different from that of Hennebique, but the court furthermore declared Hennebique's patent void because it duplicated significant features of the Monier patent and its attachments.[37]

In 1898 Thomas A. Edison took a look at the cement plant he had established a few years before as an offshoot of his ore-milling investments. By 1902 the Edison Portland Cement Company had spent 1½ million dollars on its newly opened New Jersey plant. Three years later the investment had doubled and it was reported by accountants that the sizable plant, covering an area of 80 acres, could only hope to be profitable and efficient in operation when orders were more numerous and prices were high. Edison's reaction was to search for a way to increase the demand for cement, and from this came his interest in the design of concrete housing.[38] A series of house designs were developed during his experiments.

The system that Edison pursued in all cases involved the assembly of metal formwork to make a mold for the entire structure, doing away with the piecemeal, level-by-level process of placing formwork and pouring concrete (figs. 7.9, 7.10). The problem was the development of a mixture and a method by which concrete could successfully make its way into the far corners of a form so complex, without there being voids and weaknesses that might affect the soundness of the structure. As in many of Edison's projects of this period, claims and doubts have produced an intricate web of narrative, and one of the simplest evaluations was that made collaboratively by two civil engineers who were sent by the journal *Cement Age* to visit Edison's laboratory at West Orange, New Jersey. One engineer represented the National Association of Cement Users, the other the Association of American Portland Cement Manufacturers. The engineers' reports, as published in 1908, describe many of the characteristics of the scheme, but some features are not defined, because of the changeable nature of the design, which was still in a very formative stage.[39]

The form for the house was to be made of cast-iron plates, varying from ½ inch to ⅞ inch in thickness. Inside surfaces of these plates were nickel-plated or surfaced with bronze where particularly fine detail was desired. Within the mold, reinforcing rods ½



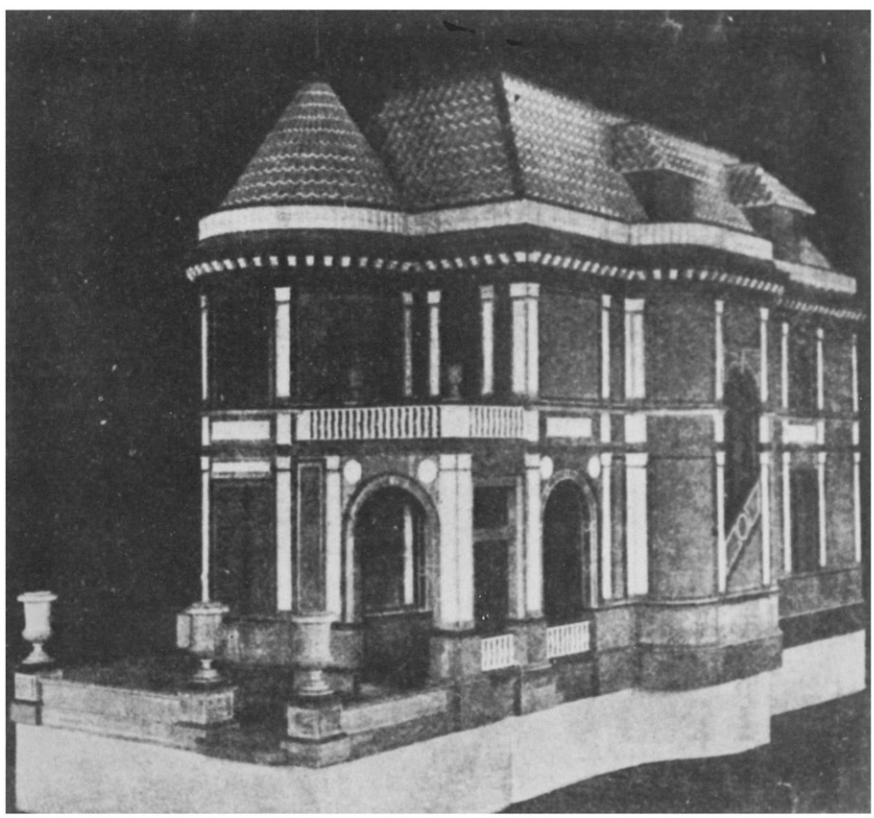
7.9 Edison's patent for concrete construction was a simple proposal. A metal mold for the entire structure would be assembled and concrete poured in at the top. (*Cement and Engineering News*, January 1924.)

7.10 This is one of several designs for Edison's concrete houses. Other designs had more pronounced delineations of shapes, and this one may have been a relatively conservative effort to simplify the flow of concrete in the form. (*Scientific American Supplement*, 18 April 1908.)

and ⅝ inch in diameter were placed, and all gravel was screened through a half-inch sieve so that there would be less likelihood of clumps of gravel preventing concrete's penetrating all parts of the form. Because the concrete mix was necessarily liquid, Edison added a colloid—in this case a clay—to prevent separation of the ingredients.[40] The flow of concrete had been tested in several small-scale molds, and at the time of the engineers' inspection a larger test was being made with a U-shaped mold that had a 4-inch-square cross-section throughout, a horizontal run of 26 feet, and vertical legs 10 feet high. When Edison poured his concrete into the top at one end of the mold, it flowed across the horizontal and rose 4½ feet in the other vertical.

The engineers were unable to examine the concrete and determine its quality, since forms had not been removed at the time of their visit. Judgments of both engineers very strongly questioned the optimistically low estimate of cost that had been provided by Edison, and both were concerned about the separation of ingredients as the concrete flowed through the mold. One of them concluded that it was "entirely unlikely that in such a mixture a concrete of 1:3:5 proportions in flat slab construction would even be self-supporting at the end of six days," and rapid removal and reassembly of formwork was the key factor in the low cost that Edison predicted for houses built as a group.[41] The project did not achieve Edison's goal and was abandoned.

Advances in the theory and practice of reinforced concrete construction meant little until technical information reached engineers in a form that could be readily employed. At the Ecole des



7.11 With a steam engine driving the equipment, the mixing of concrete in the 1860s made little provision for accurately measuring ingredients. (F. Beckwith, *Report on Béton-Coignet*, 1868.)

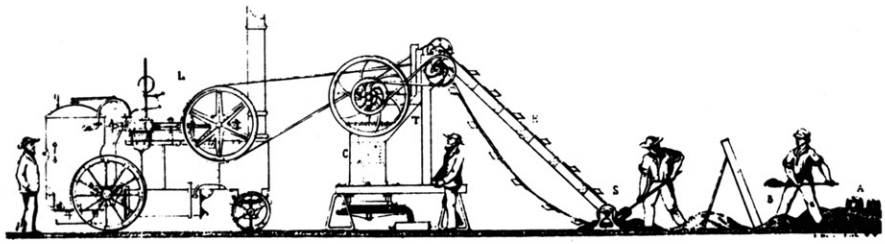
Ponts et Chausées, still one of France's principal schools of engineering, formal instruction in the design of reinforced concrete was begun in 1897 by Charles Rabut; but, on the whole, publications kept engineers informed long before professors did.

An 1871 report on the Coignet system of *béton aggloméré* was published in Washington by Major General Q. A. Gillmore, and little appeared through the next 15 years except Thaddeus Hyatt's privately published book of 1877. The formulas developed by Koenen for the German owners of Monier's patents were published in a periodical in 1886 and as a pamphlet the following year. In Germany and Austria this publication, *Das System Monier*, encouraged many engineers to investigate particular aspects of reinforced concrete design. The publications of Wayss and Company continued through the 1890s with other reports on the Monier system. Few significant publications on the subject appeared in France until late 1893 when Paul Planat, editor of the weekly journal *La Construction Moderne*, began a series of detailed articles on concrete engineering that appeared through almost a year.[42] At about the same time the British weekly *The Builder* printed a series of articles on reinforced concrete.

By the turn of the century, books on concrete engineering appeared more frequently. Many were routine repetitions of previous publications, but others were so influential that they ran through several editions and were translated into other languages. Paul Christophe, a former Hennebique engineer, published articles (later reprinted as a book) in a Belgian journal, showing detailed drawings of reinforcement placement and providing precise descriptions of a large number of projects.[43] The publications of the firms that owned patents on specific systems customarily showed finished structure without revealing details that were the firm's stock-in-trade, but Christophe's book withheld little.

A rapid succession of journals devoted to the subject of concrete construction were initiated in this period. The French organization of Portland cement manufacturers in 1896 began publication of *Le Ciment*, which combined engineering information with news on the manufacture of cement. Two years later the organ of the Hennebique system, *Le Béton Armé*, was begun. A number of American magazines (*Cement*, *Cement Era*, *Concrete*, and *Cement Age*) appeared in the first four years of the new century, and during that period two influential journals were started in Germany. Great Britain's first significant journal, *Concrete and Constructional Engineering*, did not commence publication until 1906, the delay a result of Britain's late activity in reinforced concrete construction.

Each country had its own standard books and manuals, although translation soon came to those that proved most useful. In 1902 Wayss and Freytag, concerned about the spread of so many theories other than their own, published *Der Eisenbeton*, written by the company's technical director, Emil Mörsch. Six years later it was translated and became a standby in English-speaking countries. Buel and Hill's *Reinforced Concrete*, published in New York, became popular for its middle section, which gave structural details of about 200 projects ranging from foundations to smokestacks. Charles F. Marsh's British book compared the different systems then in common use, focusing largely on Continental work.[44] Each handbook had its own virtues, but none could be complete because of the wide range of systems, theories, and practices at that time.



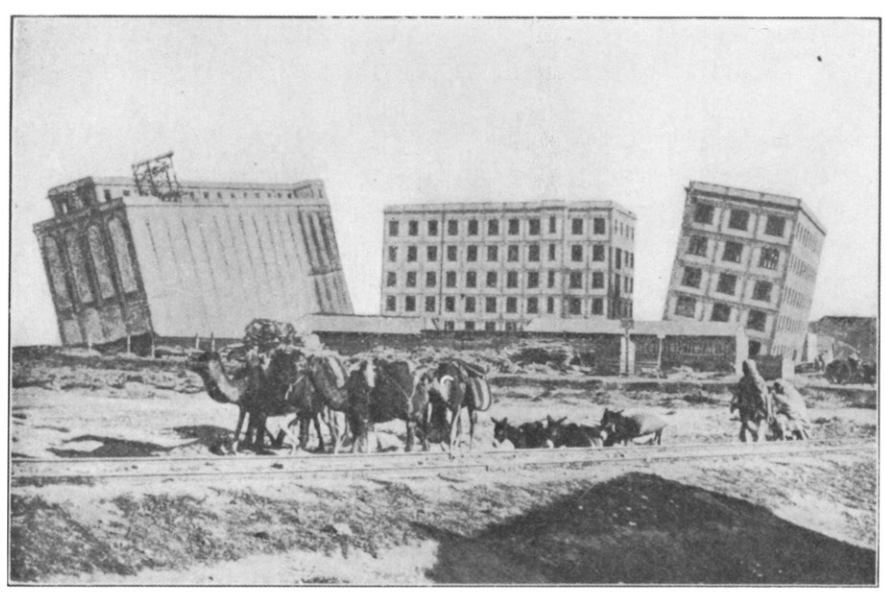
Loading tests and laboratory analyses were able to reassure many skeptical engineers and building officials about the strength of reinforced concrete construction, but the material's durability could only be truly substantiated by time. There were relatively few examples dated before 1880, and at the turn of the century there were many questions unanswered, particularly those about the possible damage that could result if reinforcement rusted. A 1905 report on advances in the use of concrete in Holland summarized the skepticism of a Dutch military engineer who opposed the use of reinforced concrete: "If the tension of the iron bars is allowed to surpass 200 or 300 kg. per sq. cm., fissures will appear in the concrete, which are sure to bring down the construction in the long run, when the iron has decayed by rust. . . . on the other hand, when less than 300 kg. of tensional resistance per sq. cm. is utilized from the iron skeleton, its presence is not to be defended from an economical point of view, and unarmed concrete might do as well."[45] The economic problems vanished as cement decreased in cost, but the fear of rust remained. Stories abounded about shovels, hammers, and muskets found unrusted in old concrete. In an informal discussion held at the 1902 convention of the American Society of Civil Engineers, there were proposals that reinforcing steel be sandblasted, painted with various waterproofing substances, or electroplated with copper or aluminum.[46] About 10 years later, members of the Science Committee of Britain's Concrete Institute visited France, where a roof slab that had been laid by François Coignet without waterproofing was opened by his son Edmond. The iron I-beams in the slab were found to be sound and unrusted after 60 years.[47]

Prior to the introduction of reinforced concrete, almost all construction procedures involved establishing physical relationships between objects that were supplied to the building location. But in concrete the material itself was formulated by workmen at the construction site; thereby the construction industry undertook "manufacturing" in addition to its customary procedures of assembly (fig. 7.11). With reinforced concrete, success depended on both the preparation of concrete and the accurate placement of the reinforcing metal—always assuming, of course, that the engineer's instructions were satisfactory. In 1903 the *Engineering News* stated its editorial opinion: "There is no doubt that a great deal of concrete work is

built by men who are really not competent to undertake it, and that much work is done without sufficiently strict and continuous expert supervision to ensure the best and safest results. In view of the enormous increase in the use of concrete, and in the variety of purposes for which it is used, it is well for engineers to bear these facts in mind."[48] Fifteen years later the American Railway Engineering Association published a study of failures of concrete structures and classified them according to the most frequent causes: improper design, poor materials or workmanship, removing formwork too soon, and such external factors as fire and the uneven settlement of foundations.

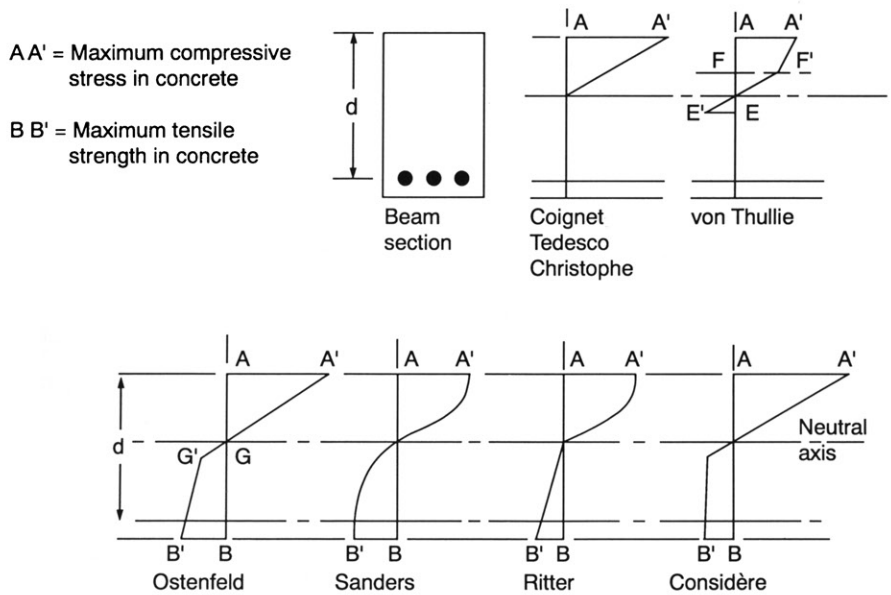
At the 1900 Paris Exposition much attention was given to the concrete work of François Hennebique and Edmond Coignet, but newspapers around the world also carried news of the failure of a concrete footbridge on the grounds of the Exposition. The following year one wing of a five-story hotel in Switzerland collapsed while under construction. Workmen had poured concrete piers beneath a previously built concrete beam without supporting the beam adequately, but an investigatory board also found that the first-story columns had been designed too small, unwashed sand and gravel had been used, and other faults of construction had been permitted. When a two-story building being built for the Eastman Kodak Company in Rochester, New York, failed in 1906, careful examination showed that, although the collapse could be attributed to removing formwork before the concrete was ready, there were inescapable indications that a poor quality of cement had been used and wood chips, leaves, and other obvious impurities were found in the concrete.[49]

Because of these and many other failures, it was not uncommon for structures to be submitted to the most direct method of testing, the actual loading of slabs and beams. The Superintendent of Buildings for the Borough of Manhattan issued regulations in 1903 that required: "The contractor must be prepared to make load tests on any portion of a concrete-steel construction, within a reasonable time after erection, as often as may be required by the Superintendent of Buildings. The tests must show that the construction will sustain a load of



7.12 A Hennebique publication early in this century showed grain elevators in Tunis, which had tilted as much as 25° from the vertical because of unequal settlement. It was claimed that by loading the high side of floors and excavating under the higher parts of foundations the buildings were returned intact to a vertical position. (*The Hennebique Armored Concrete System,* circa 1908.)

7.13 In a relatively short period all of these theories attempted to explain the role that concrete played in a reinforced concrete beam. At the top of each graph the compressive action of the concrete is indicated, and at the bottom its response in tension. These remain arguable points in structural theory. (S. B. Hamilton, *A Note on the History of Reinforced Concrete in Buildings,* 1956. Building Research Establishment, U.K.: Crown copyright 1956.)



three times that for which it is designed without any sign of failure."[50]

As the use of reinforced concrete increased, professional organizations and governmental agencies moved to bring order to the extraordinary variety of theories, formulas, and practices that were employed (fig. 7.13). The German organization of architects and engineers, along with the German Concrete Association, in 1904 issued a preliminary draft of rules to govern the design, execution, and testing of reinforced concrete construction, and these rules became the basis of regulations that were promulgated shortly afterward by the Prussian government.[51] The regulations mandated examination of projects by building authorities, and their reports were to be utilized two years later in a review of the regulations. French regulations, as imposed two years later, were liberal, with the expressed desire of avoiding discouragement of experimentation and advances of technique. Maximum stresses allowed for steel, iron, and different qualities of concrete were stipulated, and other constants were specified—all conservative values, even for that time. In reviewing parts of the proposal, the editor of *Le Ciment* commented:

> [Under these rules] the calculated bars in compression [in a beam] may be found often more important than those in tension, which appears absurd. In fact, applying the same rule to pillars, nothing hinders the provision of a metal section sufficient for resisting the load without any assistance from the concrete. . . . The men of science who elaborated these rules did not forget that some builders had already created their art, both practically and theoretically, a long time ago, and they wisely decided to limit their stresses, and in avail-

ing themselves of the knowledge [gained] by the leading constructors, to present the teaching of practical experience in scientific form, in order to prepare easy methods of controlling the works designed and carried out by less skilled men.[52]

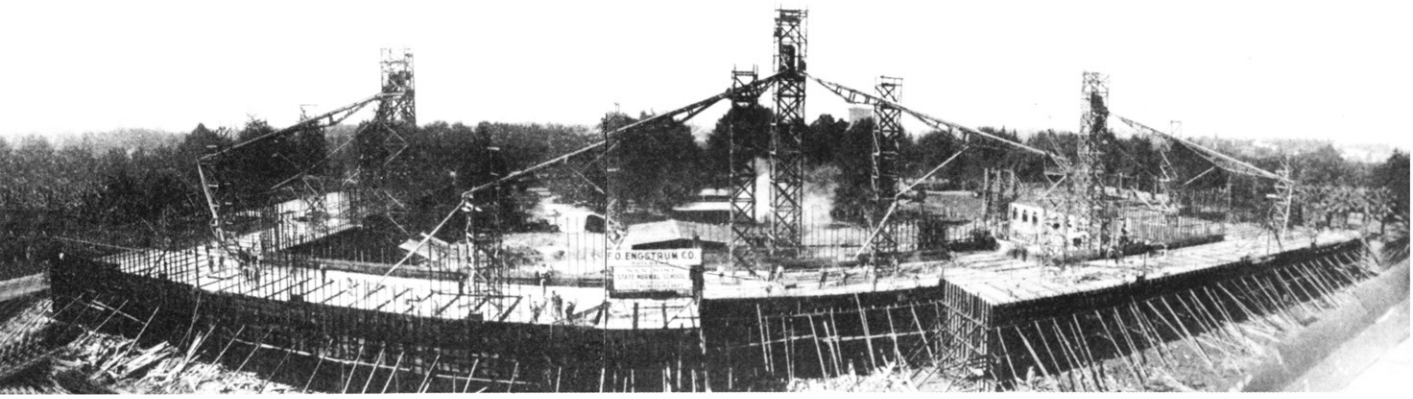
In the same year the Royal Institute of British Architects appointed a Reinforced Concrete Committee which, with the support of other organizations and governmental agencies, was to investigate requirements for concrete construction. The British Fire Prevention Committee also designated a committee on the subject, and these groups were joined by reinforced concrete firms to form the Concrete Institute. From members of this organization there was assembled a Joint Committee, which issued its first report in 1907 and continued to revise it through the four years that followed. In many ways the stipulations of the report followed the example of the French regulations of 1906, which had been in several parts influenced by the publications of Armande Considère and Paul Christophe. When the London County Council in 1915 enacted regulations for the metropolitan area, there were but a few significant variations from the Joint Committee's report.

Standards for the use of reinforced concrete were developed in the United States by a Joint Committee, which included representatives of the American Society for Testing and Materials and the national organizations of civil engineers, railway engineers, and cement manufacturers. Taking a less sanguine view of the situation than their European counterparts, the U. S. Joint Committee found the results and interpretations of tests often inconclusive and decided to institute a program of fundamental research, marshaling the resources of 11 universities.[53] In 1903 there began seven years of laboratory tests, followed by five years of testing actual buildings. When it was released in 1917, the final report received strong criticism. Still, when a new code was issued eight years later, the 1917 regulations were remembered favorably. "The old Joint Committee Report was conservative in some respects but in [its] breadth of view it was a remarkable document as compared to the present report."[54]

Until almost the turn of the century concrete was usually used as a mixture so dry that, even after it had been dropped from a height, workmen tamped it to form a solid and unified mass. Traditional formulas, stated as a ratio of cement, sand, and stone, used a 1:2:4 mix. Several factors influenced the choice of proportions: a stiff mix with more stone was usually less costly; a mix with more water and cement filled the formwork more easily; and a denser mix was stronger. It was the accepted theory that sand should fill all voids between stones and that cement should only fill voids remaining between the grains of sand, and handbooks provided lengthy instructions on the gradation of stone sizes. As late as 1904 a specification assumed a stiff mixture, saying that it should "be of such consistency that when dumped in place it will not require much tamping."[55] In 1892 and 1897 a French government laboratory published the results of tests in which it was found that, when other factors were kept constant, the compressive strength of concrete varied with the square of the ratio between the amounts of cement and water.

Because of the honeycombing that resulted from inadequately compacted dry-mix concrete, contractors and engineers began employing a more liquid mixture. The rising costs of labor encouraged contractors to find a mechanical means of distributing mixed concrete to its formwork, and the growing importance of hoists and

7.14 A panoramic photograph of the construction of the State Normal School, San Jose, California, shows five towers and seven metal chutes used to bring concrete to all parts of the project. Chutes of this sort often extended well over 400 feet. The concrete was hoisted to the top of a tower, and there it was dumped into a tube through which it flowed to the point from which wheelbarrows would take it to the formwork. (*Architect and Engineer of California*, April 1910.)

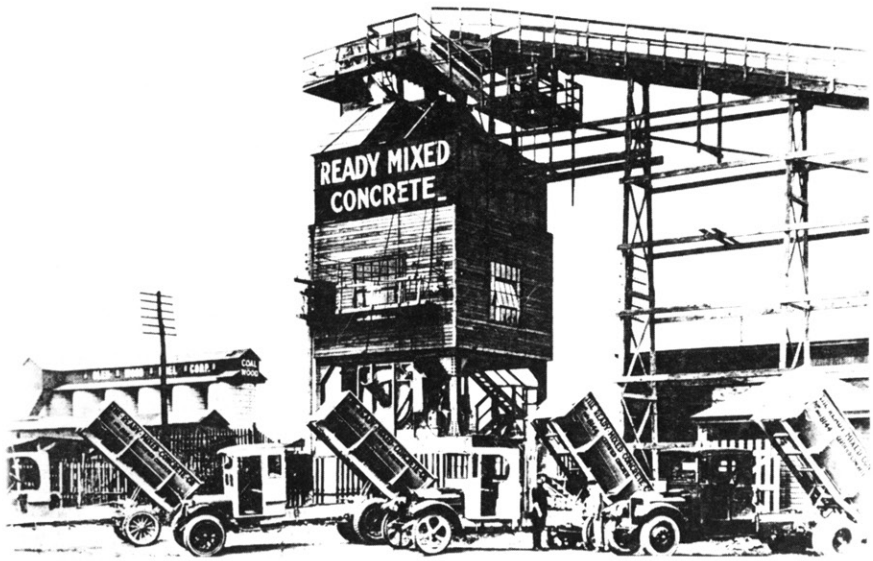


derricks on construction sites led to the use of chutes and tubes. With a hoist tower at a central point where concrete was mixed, the concrete could be lifted to the top of a tower and there poured into chutes that extended as far as 500 feet from the hoist. If several chutes were provided, concrete could be directed alternately to several places about the project, from which wheelbarrows would take it the remaining distance to the formwork (fig. 7.14). A California maker of such equipment in 1910 boasted: "The old wheelbarrow method of mixing and distributing the cubic yard is from 60 cents to $1; by the use of carts, runs from 40 cents to 75 cents; by the use of 'Gravity System' it costs from 15 cents to 25 cents."[56] Such use of extremely fluid mixes appears to have been very much a phenomenon of American practice, and seldom seen in Europe. Wetter mixes offered a more watertight concrete and seemed advantageous in a period when there was great controversy about whether reinforcement rusted within concrete. Although stone tended to settle to the bottom of wet-mix concrete, producing a mass of uneven quality, American engineers and contractors strongly favored the generous use of water, particularly during the "wet-mix era" between 1905 and 1910.

Studies published in 1912 showed that excessive amounts of water reduced the density of concrete, thus lowering its strength. Six years later, when Duff Abrams issued his report on almost 50,000 tests, the matter seemed to have been settled, although the conclusion was perhaps overstated:

> The size and grading of the aggregate [stone] and the quantity of cement are no longer of any importance except insofar as these factors influence the quantity of water required to produce a workable mix. This gives us an entirely new conception of the function of the constituent materials entering into a concrete mix and is the most basic principle which has been brought out in our studies of concrete. . . . The equation expresses the law of strength of concrete so far as the proportions of materials is concerned. It is seen that for given concrete materials the strength depends on only one factor—the ratio of water to cement.[57]

By the time the water-cement ratio had been fully accepted as a critical factor, it was recognized that, while that ratio determined the fundamental



7.15 The quality of concrete mixes was often much more carefully controlled after the introduction of ready-mixed concrete in the 1920s. Here hydraulic dump trucks wait to load. (*Pictorial History of the Ready Mixed Concrete Industry*, 1964.)

7.16 The Cottancin system, used in this Paris factory, was one of about 21 reinforced concrete systems being applied in France around 1909. Cottancin did not believe the bond between concrete and steel was reliable, and therefore his system employed very narrow beams that were reinforced with a carefully woven mesh of wire. (*Concrete and Constructional Engineering*, July 1906.)

7.17 Anatole de Baudot proposed this design for a government building. His Gothic leanings are clearly indicated by the ribbed columns in the foreground, but in the upper structure he converts the Cottancin system into what he called "the solution through tangency." (A. de Baudot, *L'architecture, le passé—le present*, 1916.)

strength of concrete, the grading of stone and proportioning of ingredients provided a means of utilizing the ratio in an economical and workable mixture.

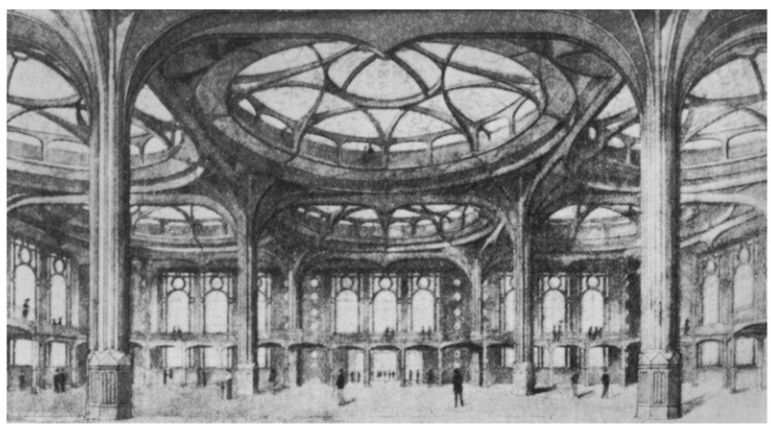
The most dramatic architectural development of early concrete construction was displayed in the church of St. Jean de Montmartre, designed by the architect Anatole de Baudot using the Cottancin system, still another patent that was challenged by Hennebique (fig. 7.16). This system was perhaps not really concrete, because large aggregate could not be used in beams so narrow. The whole web of the beams in the Cottancin system was reinforced by a woven network of wire or small round rods. Beams ran both in the customary rectangular pattern and as diagonals, and usually the diagonals were more numerous. A pattern of that nature was somewhat medieval in appearance and it is not surprising that Baudot, student and associate of Eugène-Emmanuel Viollet-le-Duc, the leading French Gothic Revivalist of the time, should find it challenging as a means of achieving large spans without the height required in arcuated systems (fig. 7.17).

Another very important consideration that is quite favorable to reinforced concrete is the ease with which it allows supports to be spread farther apart, a solution that is almost unavoidable today. Certainly we are able, like the Romans and Byzantines, to erect vaults and domes with great spans, to increase them greatly, thanks to assemblies of light-weight materials and reinforced concrete.[58]

Building authorities viewed Baudot's design with serious misgivings and, because of delays in granting the necessary approvals, the church of St. Jean de Montmartre was completed a full seven years after design was begun in 1897. When a British deputation from the Concrete Institute visited Paris around 1910 to inspect buildings in which reinforced concrete had been used, their tour included the church, and the committee found no fault with the condition of the concrete.[59]

In 1903, the year before St. Jean de Montmartre was at last completed, the first skyscraper of reinforced con-

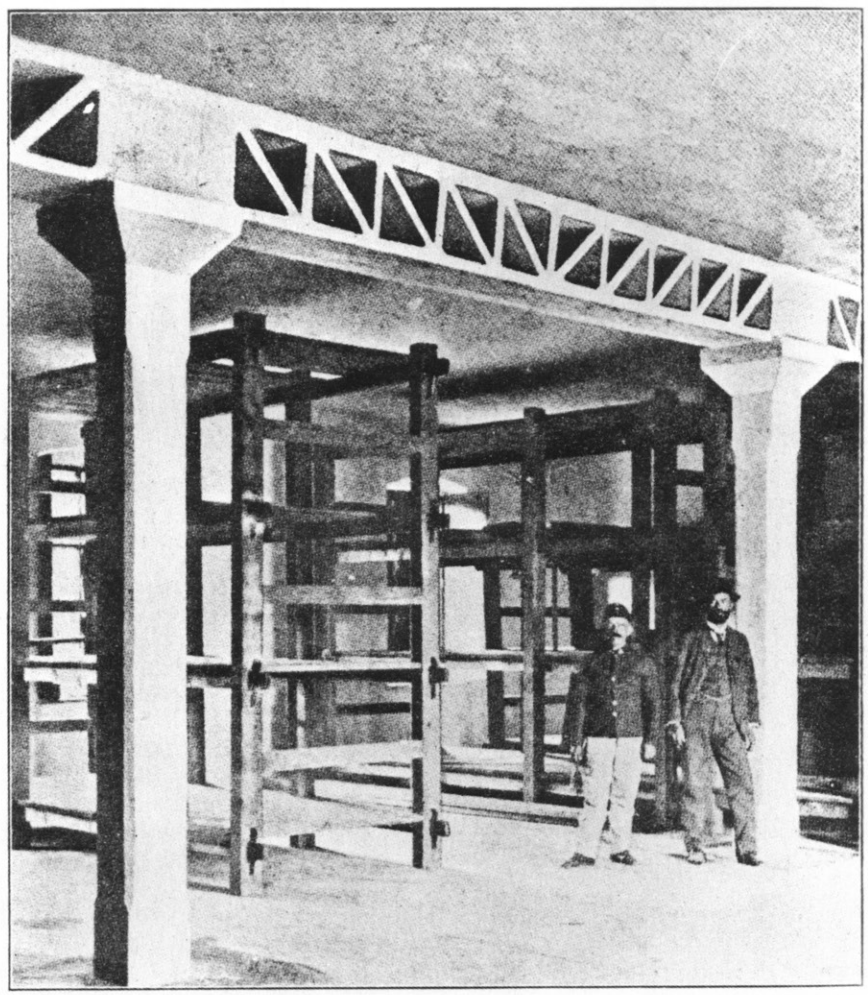
crete, 16 stories high, was built (fig. 7.19, 7.20). The Ingalls Building in Cincinnati, Ohio, was designed by the architectural firm of Elzner and Anderson, and engineering of the concrete frame was done by a Ransome licensee. Most of the building's floor area was framed in rectangular panels 16 by 32 feet, subdivided into two squares by an intermediate beam. Instead of the ribbed slab used in most of Ransome's work, the engineer made floors of concrete 3 to 5 inches thick and reinforced with twisted square rods.[60] The exterior finish of the Ingalls Building was set against concrete walls 8 inches thick, except for party walls that were 3 to 4 inches thick. The bottom three floors were faced with marble, the top story and cornice with white terra-cotta, and the stories between with gray brick.



7.18 Franz Visintini, an Austrian working in Switzerland, produced precast lattice beams, either 8 or 12 inches wide. The thickness of the bottom and top surfaces could also be varied. Larger spans and heavier loads were carried by stacking the beams two deep. (*Journal, Western Society of Engineers*, November–December 1904.)

7.19 The Ingalls Building (Cincinnati, Ohio: Elzner and Anderson, architects) occupied a site only 100 by 50 feet and its 16 floors did not achieve a spectacular height for the time. Nevertheless, it demonstrated that all the characteristics of the skyscraper, which had been developed in steel-frame construction, could be present in a concrete-frame building. (*Engineer*, February 1906.)

7.20 Attaching a terra-cotta cornice to a concrete building frame was much the same as attaching it to a steel frame. On the Ingalls Building, Cincinnati, Ohio, the walls below this cornice were of masonry. Brick was supported at each floor by a 3-inch projection of the floor slab. (*Engineering Record*, 23 May 1903.)



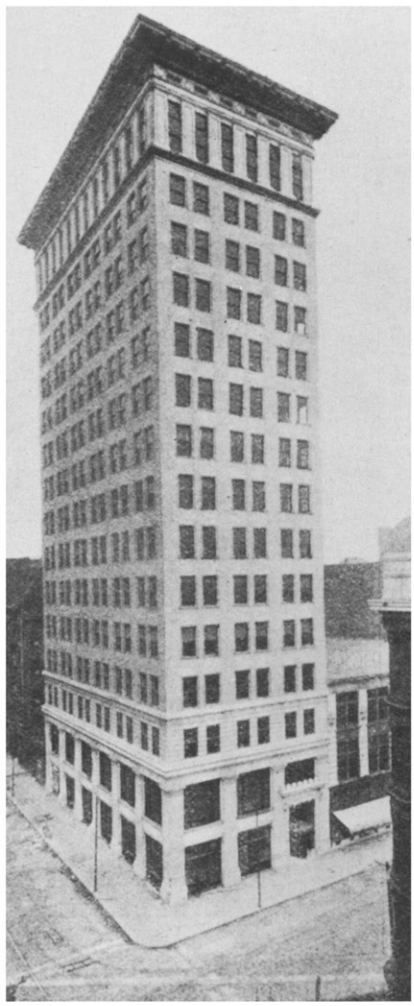
However, the architect considered such coverings to be superficial:

> It is not incumbent upon us to face the concrete with marble, or brick and terra-cotta, as was done in the Ingalls Building, for reasons of momentary expediency, for as the state of the art advances, the architectural forms, moldings and what not, will be incorporated with the molds for the structural work, and upon removing the formwork, the surface of the exposed concrete, will be given the desired finish of rubbing or tooling, as the case may be.[61]

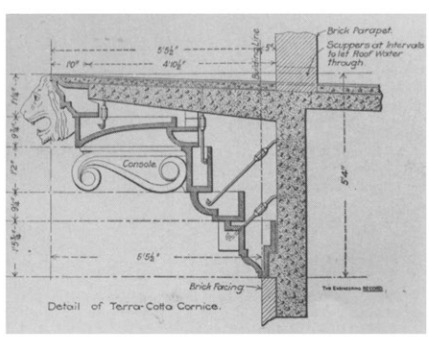
With the Ingalls Building the experience with fireproofed steel office buildings was transliterated into the techniques of reinforced concrete.

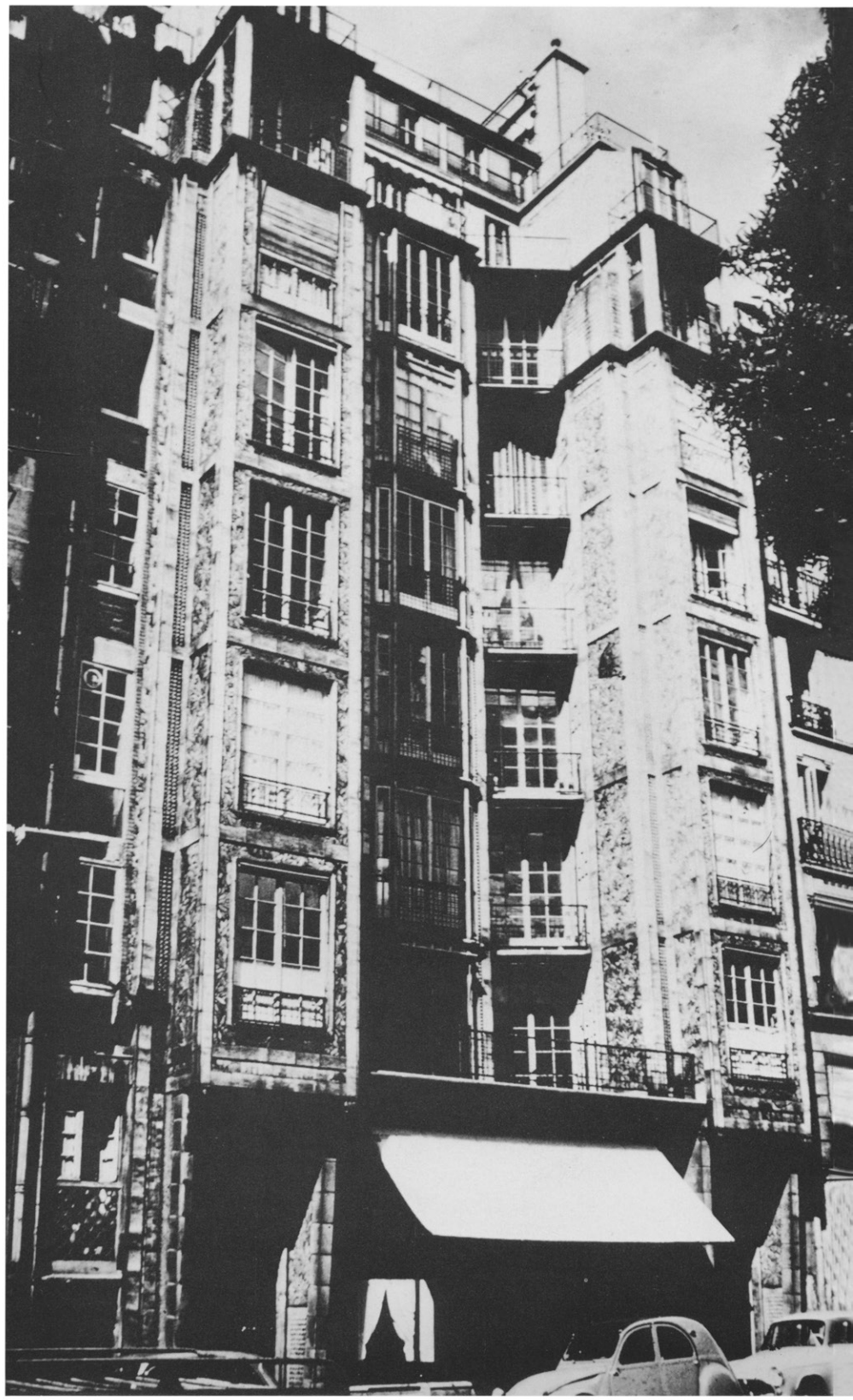
The Ingalls Building looked like any other office building of that time. On the outside, masonry concealed every line of the concrete frame; on the inside, plaster covered the structure. At the same time that the Ingalls Building was under construction in Cincinnati, Auguste Perret was building his first reinforced concrete frame structure, an apartment building at

25b Rue Franklin, Paris, which was to be occupied by Perret's parents and offices of the family construction firm. Like Hennebique's offices on Rue Danton, this project was required to make the most of a small site, and reinforced concrete seemed a logical way to avoid thick walls of masonry that would occupy precious floor area. Perret in 1936 explained his treatment of the exterior: "It was the first house built of reinforced concrete and exposing its skeleton, as it is done today. At that time I thought that in order to preserve the steel it was necessary to cover it with a facing. The proper material seemed to me to be tile, but I used the tile in different patterns, depending on whether it was used on columns or walls, outlining in this way the skeleton."[62] Flat tile covered the concrete frame, and the masonry curtain walls bore slightly darker tiles stamped with a floral pattern (fig. 7.21). Although the facade angles in and out in order to capture as much light as possible from the narrow frontage, there is a classical severity in the design, except for the hint of Art Nouveau in the floral pattern of some tile. Perret and his family were engaged in construction, but for this project the work in concrete was executed by a subcontractor who was familiar with the Hennebique system.[63] From that time Perret's work, including auditoriums and industrial buildings, explored the structural and visual characteristics of reinforced concrete construction. The material suited his interests in structure—"the architect's mother tongue," he called it. Two decades after his apartment building on Rue Franklin, Perret designed his crowning achievement in the use of concrete, a church in Le Raincy, an industrial suburb of Paris. There the framework was exposed, even showing the pattern of planks used in the formwork. Peter Collins



has pointed out the contrast between the opinions of an architectural periodical which believed the church was "the most significant building since Henry Labrouste's reading room in the Bibliothèque Nationale" and a civil engineering journal which insisted that the concrete should have been concealed behind some veneer of more proper materials.[64]

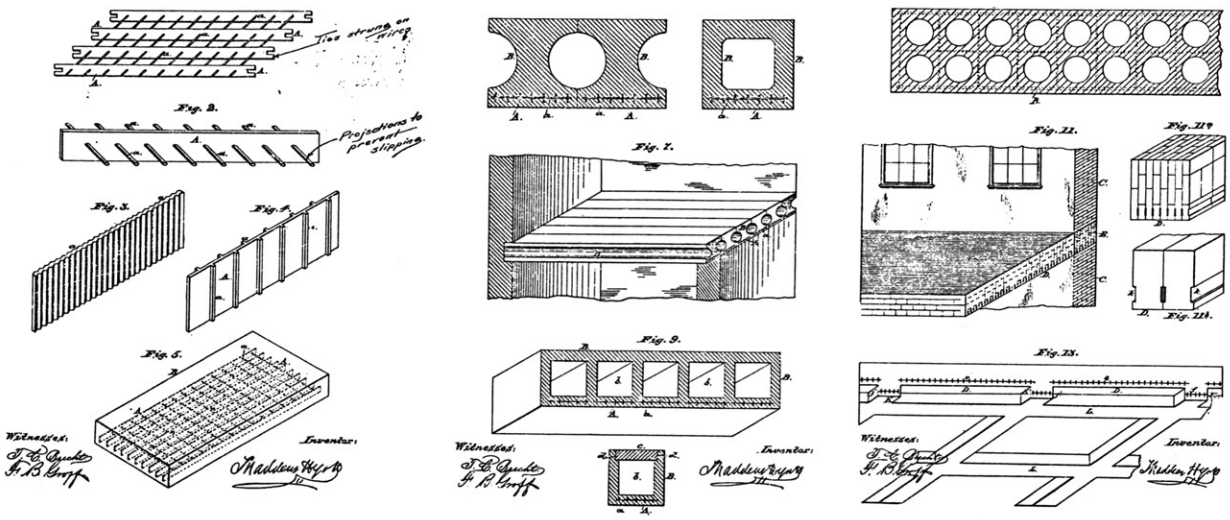




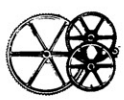
7.21 Auguste Perret covered the concrete frame of the apartment building at 25b Rue Franklin (Paris, 1903) with tile and used tile with a floral pattern on the wall panels. Because of his need to gain the maximum amount of light through the narrow facade, windows are more evident than the patterned walls. (Courtesy of Architectural Library, North Dakota State University.)

7.22 Thaddeus Hyatt's 1878 patent shows his grid of reinforcement and some of the precast units that were included in the patent. Besides reducing a floor's weight, Hyatt explained that the holes in some of these floor systems could serve as "longitudinal flues or ventilating spaces." (U.S. Patent no. 206,112.)

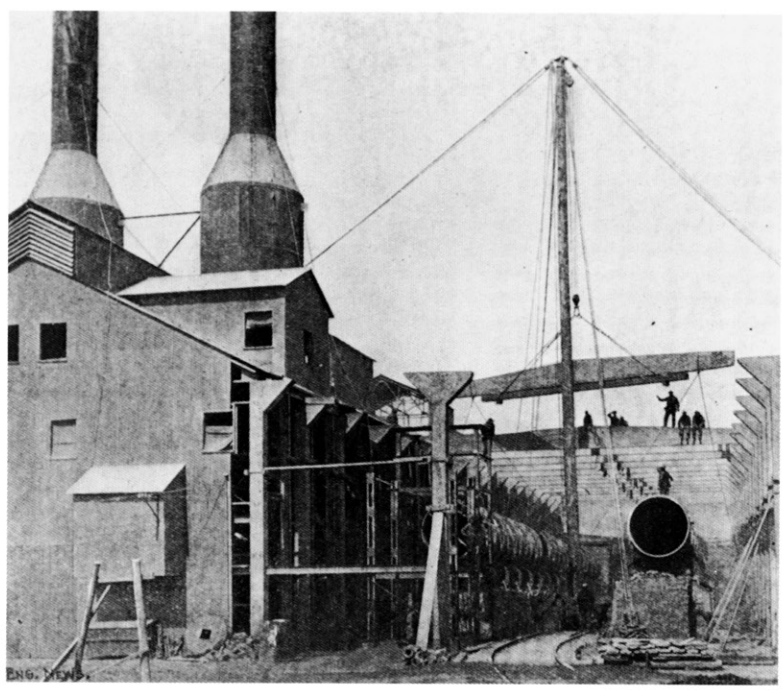
7.23 Two kiln houses for the Edison Portland Cement Company were constructed in 1907 with precast columns, roof slabs, and girders 50 feet long. Rotary kilns for cement making are shown inside. (*Engineering News*, 4 July 1907.)

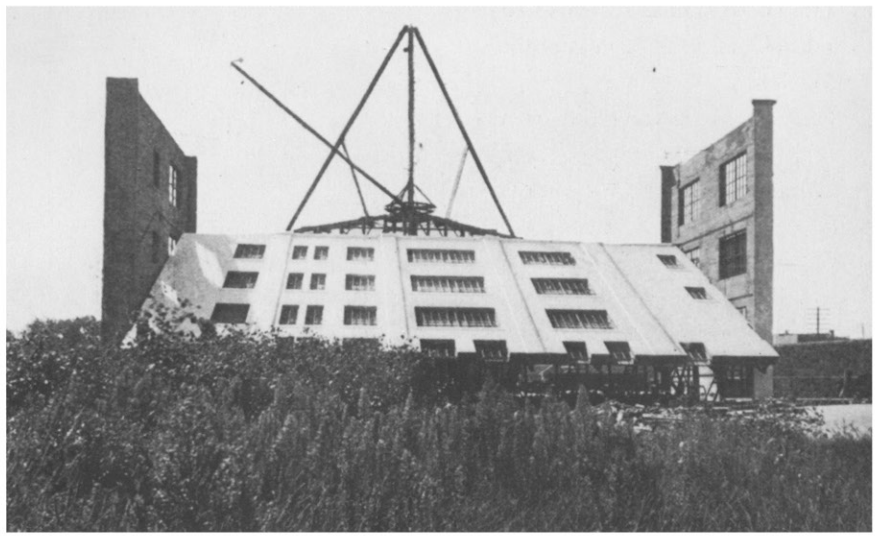


The works of Auguste Perret were not structurally adventurous and his designs, no matter how daring in other ways, had a traditional air. His contemporary, Tony Garnier, as architect for major projects of the socialist city government of Lyons, moved closer to the forms and methods of the future. Together, Perret and Garnier established reinforced concrete as the dominant medium of modern architecture in France.



Beams, columns, and floor slabs of precast concrete were as elementary to construction as the traditional stone blocks and heavy timbers. Hyatt's patents of the 1870s show precast planks and beams spanning between walls—not surprising since his business was manufacturing sidewalk panels (fig. 7.22).[65] In 1900 a stable was built in Brooklyn, New York,





7.24 A factory in Rogers Park, Illinois, was completed by lifting four wall sections, each 40 feet high. Floor slabs were cast in stacks of about 30, and after they were set in place a covering of concrete was carefully leveled for the floor surfaces. (*Scientific American Supplement*, 9 December 1911.)

7.25 John Brodie's Liverpool housing employed a variety of panels with their notched edges dovetailed together. The floors had an inlaid finish of wood, and the walls were prefinished, some having color in the concrete. (*Journal, Royal Institute of British Architects*, September 1969.)

using precast roof decking 2 inches thick. Concrete slabs, 4 feet wide and 17 feet long, were secured to steel roof trusses, and similar panels served as partitions within the stable. [66] A more complete use of precast concrete was made in a four-story factory building constructed five years later in Reading, Pennsylvania. The factory's walls were brick and concrete columns were cast in place, but the roof and floors were carried by precast girders 24 feet long holding beams that spanned 12 feet. To reduce their weight, both girders and beams were perforated in a trusslike pattern.

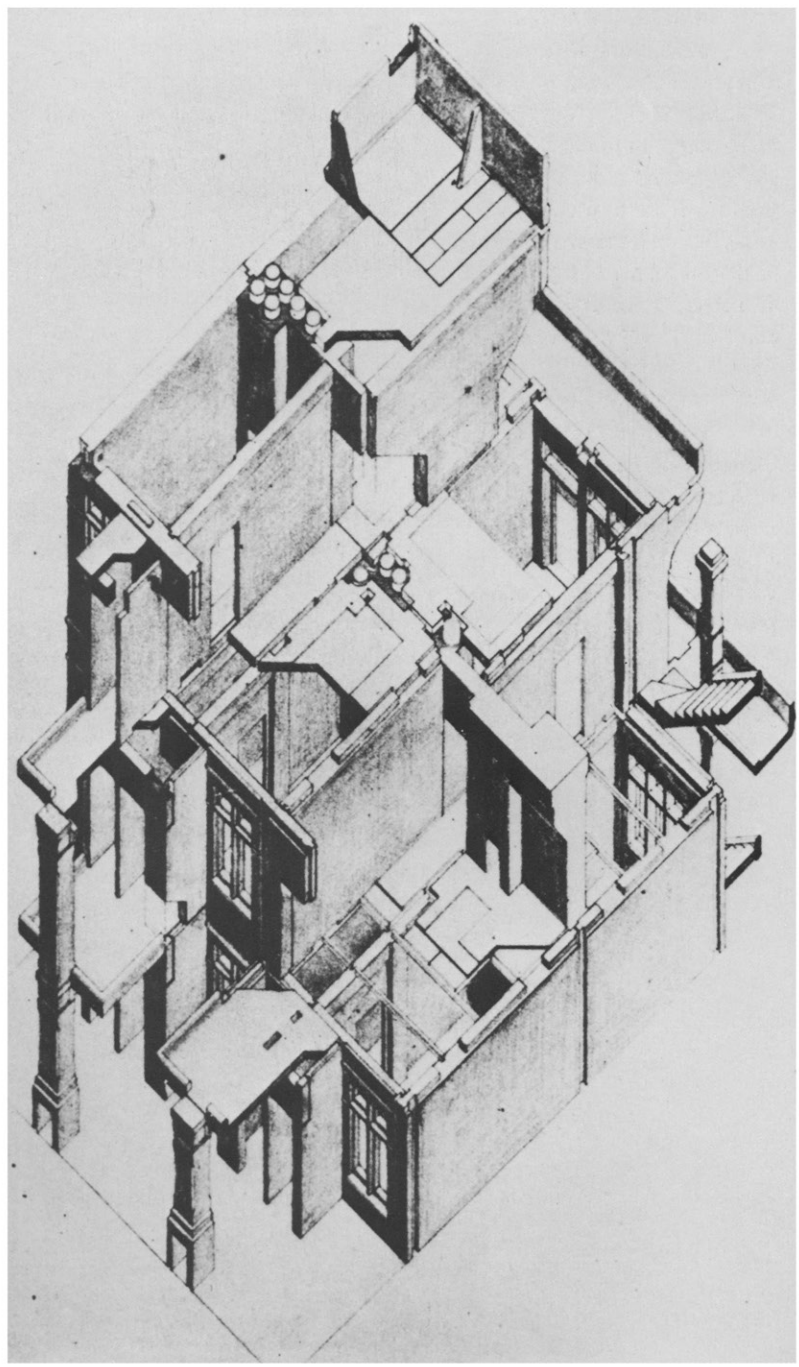
Little formwork was needed when slabs were to be precast. The roof slabs employed in 1907 for the Edison Portland Cement Company, New Village, New York, were molded one on another with layers of paper as separation (fig. 7.23). In other cases, a coating of liquid soap was painted between to keep slabs from bonding to the ones beneath. By 1910 there had even been methods developed for casting panels in which the two surfaces of concrete were separated by an air space. In the United States the procedure used for constructing a cavity wall as a single panel involved first pouring a slab of concrete about 4 inches thick; then adding a layer of paper, 4 inches of sand, and another layer of paper; and finally adding 4 inches more of concrete (fig. 7.24). Connections between the two concrete surfaces were made with metal brackets or by removing portions of the sand layer.[67] As such panels were tilted to their intended position, rods were employed to make sand flow from the center.

In 1903 John Brodie, city engineer of Liverpool, presented his scheme for building less costly housing for the poor to the city's Housing Committee.[68] Eighteen months earlier Brodie had begun experiments with concrete containing clinkers from the furnaces of the Liverpool waste disposal system. As shown in his 1901 patent, Brodie employed precast concrete panels, whether walls or floors, with notched edges, the tenons arranged so that four walls could interlock along the same line (fig. 7.25). In this way the intersections of panels formed stiff verticals, eliminating the need for columns. The underside of floor panels had ribs that curved to an increased depth at the center of the panel.[69] Several tenements, stables, and an exhibition cottage were built between 1904 and 1906 using this system. Although the system was short-lived, Brodie's successes were widely known

and influenced similar systems that were developed in Holland and the United States.

"Unit system" became the general term for construction methods using precast elements during the period before World War I. Systems for housing proliferated, although none were to affect significantly the accepted manners of constructing residences. Ernest L. Ransome developed the "Ransome Unit System," a method of constructing factory buildings and warehouses with precast concrete. For a four-story building erected in 1911 for the United Shoe Machinery Company of Beverly, Massachusetts, Ransome designed concrete columns, girders, beams, and wall panels that were all precast. Floor and roof surfaces were poured in place, and they did much to unify the assembled parts.

A more involved system was based on the many patents taken out by John E. Conzelman in the years from 1910 to 1916 (fig. 7.26). The "Unit Structural Concrete Method," as developed by his Unit Construction Company of St. Louis, Missouri, was principally utilized for industrial and railroad buildings. A major early (1911) application of this unit system was the five-story building of the National Lead Company, St. Louis, Missouri.[70] The structure was entirely assembled of precast elements, and it was designed to withstand floor loads of 500 pounds per square foot. Five years later a far different project was undertaken by Conzelman's firm for the Youngstown Sheet and Tube Company in the wake of fires and riots cause by workers in that Ohio city. In tardy response to their workers' housing problems, the company constructed 281 residential units with Conzelman's unit system. Part of this housing remained in use over 60 years after its construction.[71]



7.26 The Unit System developed by John E. Conzelman of St. Louis made use of more than 51 U.S. patents he obtained from 1910 to 1916. Applications of the system were mostly industrial and railroad buildings, although in 1914 about 50 shelters were constructed for passengers along the Pacific Electric Railway in Los Angeles. (*Journal, American Concrete Institute*, February 1954.)

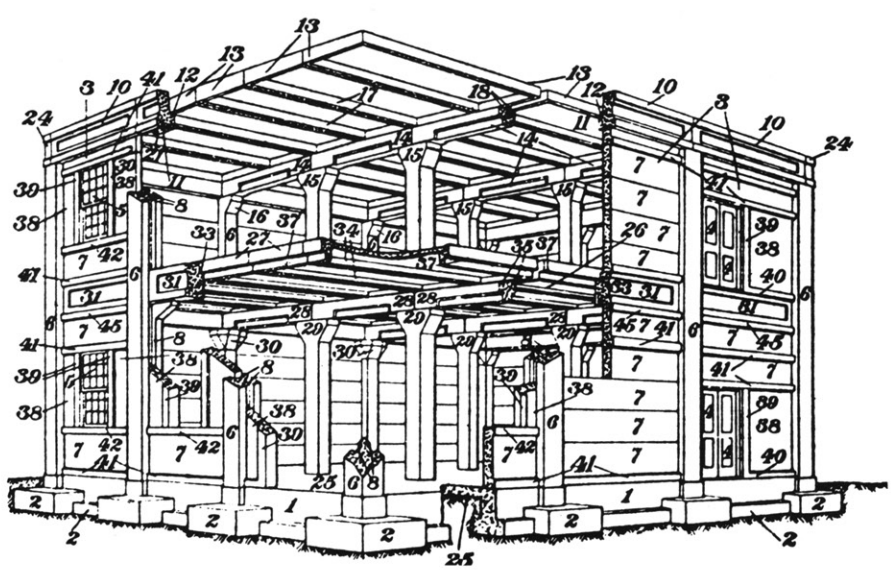
7.27 In C. A. P. Turner's publication of his flat slab system of construction, a large circle of reinforcement was placed above each column, forming the basis of a four-directional pattern of slab reinforcement. (H. T. Eddy and C. A. P. Turner, *Reinforced Concrete Buildings*, 1914.)

Most structural uses of reinforced concrete had followed the traditions of construction in other materials—columns, girders, beams, joists, and decking in a succession of elements that were a step-by-step reduction of the structural task in dimension and difficulty. An early departure from tradition was flat slab construction that dispensed with girders, beams, and joists, leaving only the column and a horizontal slab. In 1902 O. W. Norcross, the contractor on many of H. H. Richardson's buildings, was granted three patents related to a flat slab system.[72] These patents he sold to another company, which successfully defended them against a series of court challenges instituted by C. A. P. Turner, an engineer in Minneapolis, Minnesota. An article written by Turner in 1905 showed a concrete column with a slightly flared capital supporting a slab 7 inches thick (fig. 7.27).[73] The advantage most emphasized in Turner's article was the economy of eliminating the costly formwork required for beams and joists.

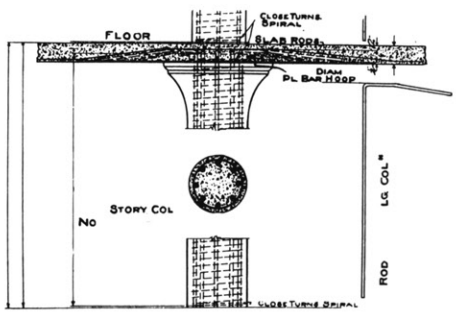
The following year Turner built the Bovey-Johnson building, five stories of flat slab construction. Minneapolis building officials insisted on testing the structure and found that almost three times the design load caused a deflection of only one-fourth of an inch. The new system proved to be popular for buildings with heavy loading, and it is reported that in the next seven years 80 percent of all buildings in the United States designed for loads of 100 or more pounds per square foot of floor area employed flat slab construction.[74]

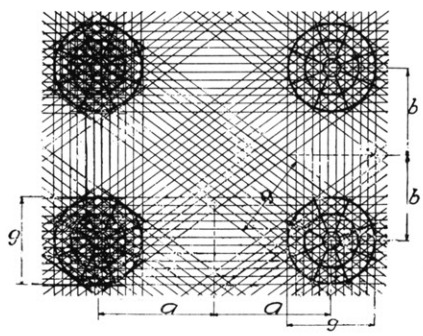
In Europe the Swiss engineer Robert Maillart experimented with mushroom columns through 1908 and 1909. His first use of the mushroom column was a five-story industrial building erected in 1910. There were two clear differences between the approaches of Turner and Maillart: in placing grids of reinforcement in the slab, the Swiss engineer followed the two directions along which the columns were aligned, while the American put equal amounts of reinforcement in those directions and along the diagonals; and while Maillart insisted on a subtle curvature blending the undersurface of the slab into the column's shape, Turner used a more abrupt juncture of the two.

By the time both Turner and Maillart were building flat slabs and mushroom columns there was an obvious need for an accepted theoretical basis for the engineering design of such

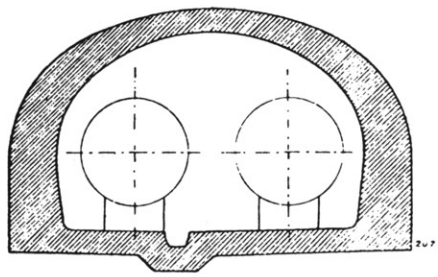


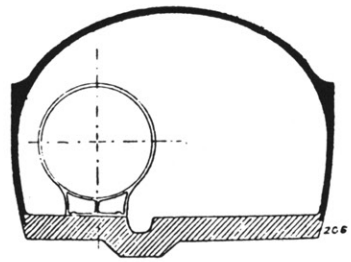
structures. Franz Grashof had published in 1866 the first explanation of a plate's action when supported by equally spaced columns, and this was the basis of several theories. Others were derived from an assumption that circles of slab around the columns acted as cantilevers and the remainder of the slab was suspended from the ends of the cantilevers. One skeptic assumed a single set of conditions and calculated slab thickness and the reinforcement according to the formulas of the six most popular theories. For all but one formula the required slab thickness was the same, but the calculated amount of required reinforcement varied as much as 400 percent.[75] The smallest amount of steel resulted from the formula used by Turner. Arguments among theorists grew bitter, with phrases such as "multifarious absurdities" and "a riotous license of figuring" hurled at opposing factions. The theorists argued vociferously, but in the previous seven years Turner had completed buildings and bridges worth $200,000,000 and cautious clients and building authorities had required the testing of many of those projects. Against practical experience the fine points of theory had little chance to survive.





The first concrete shell was a railroad station at Paris-Bercy designed in 1910 by Simon Boussiron, the engineer of several major bridges and canal projects. The vaults of the station's freight-receiving room spanned between concrete beams that were themselves large enough to span the distance and support the vaults. In a similar freight room, built the following year, it was recognized that the vaults themselves had considerable spanning capability, and the beams on which they rested were reduced to little more than the concrete necessary to adequately cover reinforcing rods. Just before World War I, concrete aircraft hangars were proposed to the French government, and the idea was revived in 1916, when eight were built of thin barrel vaults with ribs on the outside. These structures could be built quickly, and military authorities launched construction of many more designed in much the same way. The largest of this type, built in 1919, used three parallel vaults connected by a transverse vault and thus providing an unobstructed space about 395 feet by 148 feet. After the war, prospects of transatlantic transportation by dirigibles led to the construction of two hangars at the Orly airport outside Paris. The designer, Eugène Freyssinet, spanned 320 feet with a parabolic vault made of angular corrugations from 10 to 18 feet in depth. The concrete was not quite 4 inches thick.[76]





7.28 In 1892 Paris began construction of a new drainage system, with about 1½ miles of tunnel, 17 feet wide, connecting the system to fields outside the city. Masonry construction (shown at left) was first proposed, but officials chose to try the reinforced concrete design presented by Edmond Coignet, a vault slightly more than 3 inches in thickness. Success of the project did much to heighten interest in reinforced concrete in France. (*Concrete and Constructional Engineering*, July 1906.)

7.29 This hemispherical framework of metal bars was sprayed with concrete to form the first Z-D dome of thin-shell concrete. In later projects edge conditions and deflections led the engineers to build sounder formwork, which was removed after the concrete shell was completed. (W. Bauersfeld, *Projection Planetarium and Shell Construction*, 1957. Reprinted by permission of the Council of the Institution of Mechanical Engineers.)

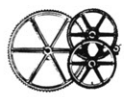
A prominent German engineer-industrialist approached the Zeiss optical works to construct the first planetarium projector for installation at the Deutsches Museum in Munich. As the projector neared completion in 1922, it became necessary that the technicians be provided with a hemispherical space in which the projector could be tested and adjusted.[77] On the roof of a Zeiss factory building at Jena, a hemispherical network slightly over 50 feet in diameter was fabricated of steel bars about 2 feet long (fig. 7.29). It had been intended to cover the dome with wire mesh and trowel on gypsum, but that water-susceptible material was discarded when a covering of sprayed concrete was suggested by an engineer associated with the construction firm of Dyckerhoff and Widmann, contractors for several buildings in the Zeiss factory complex. The frame was sprayed with concrete, with an accurately curved form held against the inside of that portion of the dome being sprayed. Between the steel bars the concrete was about 1.2 inches thick.[78]

This system was developed through collaboration of Walther Bauersfeld of the Zeiss corporation and Franz Dischinger, an engineer with Dyckerhoff and Widmann. The patented system was known in England as "Shell-D" and in the United States as "Z-D" (an abbreviation of Zeiss-Dywidag, the last part being made of the first syllables of the contracting firm's name and the German equivalent of "Inc."). Their second project was larger, a shallow dome 131 feet in span and 2⅓ inches thick. As the complex mathematics of shells was studied, similarities were found between the actions of domes and barrel vaults. The first Z-D vaulting built commercially was for a fair in Düsseldorf, barrel vaults 2 inches thick and arching almost 40 feet, with a span of 75 feet.[79] By 1927 the processes of designing and constructing thin shell structures had advanced to the point where it was possible to build the Market Hall at Frankfurt am Main, which spanned about 120 feet with concrete barrel vaults three to four inches thick.

In 1932 Dyckerhoff and Widmann allied itself with Roberts and Schaeffer, an established Illinois engineering firm, for the promotion of the Z-D system of thin-shell construction in the United States. Appropriately, their first project was a planetarium, the Hayden Planetarium of the Museum of Natural History, New York. The concrete shell was sprayed over formwork covered with sheets of cork. Inside, a white-painted ceiling was suspended, perforated sheets of stainless steel providing some protection against the acoustical problems that plague concave shapes.[80]

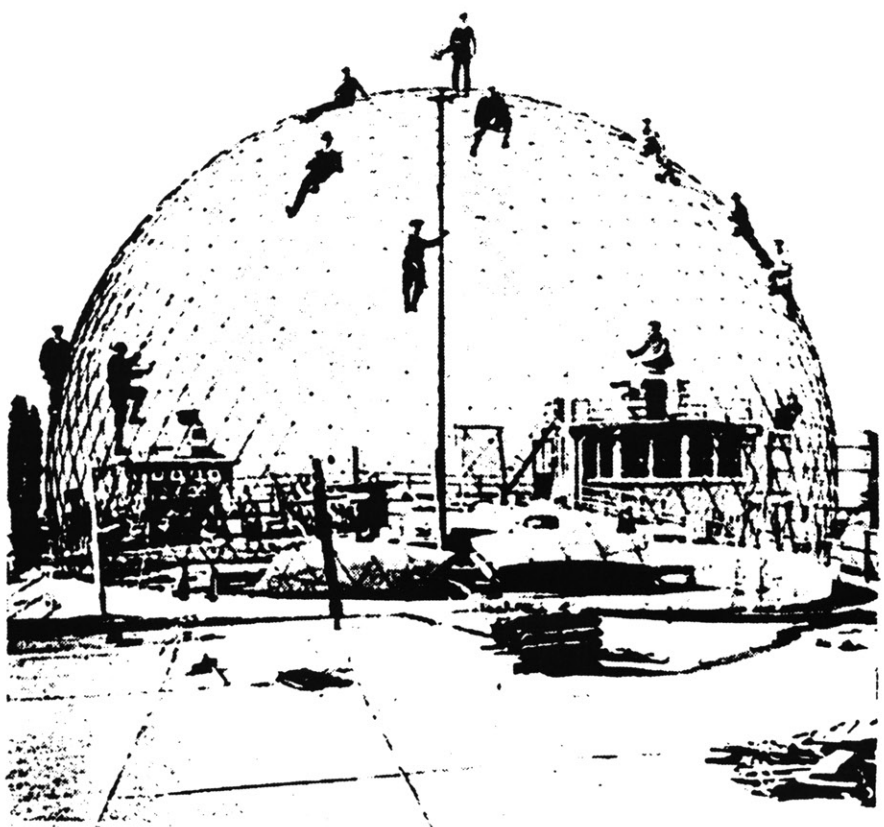
The cost relationship of labor and material in the United States was quite different from that of Europe, and the design of shell structures had to be adapted in recognition of that difference. However, because shells used little of strategic materials, they were used during World War II for factories and aircraft hangars. By the 1960s shells were seldom employed,

unless esthetic considerations called for a dramatic form.



Unlike steel, which in most buildings must be fireproofed, reinforced concrete is in itself fireproof, eliminating the necessity for a protective covering. In most parts of the western world the cost of concrete construction is about equally divided between the concrete itself, reinforcing steel, and the formwork in which the beams, columns, and slabs are poured. (Costs of formwork generally vary according to local labor costs.) In multistory building construction a steel framework, once it is protected from fire, has dimensions very near to those of a concrete framework. Therefore, the choice between the two materials for structural purposes is principally based on cost and speed of assembly.

The use of precast concrete advanced in the 1930s and 1940s when its use eliminated the mixing of concrete on the site. This advantage vanished when transit-mixed concrete came into use, and consequently the demand for precast concrete declined.[81] At present the majority of structural reinforced concrete is cast in place, developing a monolithic rigidity in the construction. Precast concrete, which for its rigidity relies on careful detailing of connections, has not yet effectively challenged the preponderant method of casting buildings *in situ*, and the Roman system of constructing molds in the form of the building has continued.



Technics and Architecture

The Development of Materials and Systems for Building

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Systems

From its very beginning, mechanization caused workers to move to cities, seeking employment in factories and mills. In England, where machines first significantly influenced national life, an increase of rural poverty and of the birth rate during the eighteenth century further encouraged the movement of population toward cities. Only about half lived in rural areas at the middle of the nineteenth century. The most industrialized English cities became such crowded and sooty tangles that they were sometimes referred to as "the Black Indies," so different from the rest of the country that they seemed strange colonial islands.

During these centuries England's shipping activity and foreign trade blossomed, almost doubling during the nineteenth century. This growth was accompanied by increasing numbers in the social level between the gentry and laborers. At the upper reaches of this middle class were major businessmen, who had wealth without station. At the lower reaches were clerks and merchants. In London between 1851 and 1891 the number of "commercial clerks" increased about fivefold, while the city's population as a whole did not even double. Members of the middle class desired to better their living conditions, both at home and at work. Their expenditures may not have been so lavish as those of the nobility or the richest bourgeoisie, but the middle class became multitudinous, a ready market for building improvements that offered comfort and convenience. Manufacturers found that working conditions influenced the output of their workers, knowledge that was gained through the leadership of a few philanthropic factory owners, the adoption of legislation, and the insistence of labor unions. A stronger incentive to improvement was the fact that in warmer and better-lighted factories work could continue through longer hours and an owner's investment in the mill and machines would thereby produce greater profits. From such industrial applications came the elementary forms of devices that were later used in buildings of all sorts.

The comfort-producing systems that were developed had as their purpose the production of an environment in which one was not threatened by actual discomfort and was, perhaps, even somewhat cosseted. For a middle-class society that frowned on excessive luxury, it was difficult to determine what was a beneficial degree of comfort. In a period of radical change in the principles of medicine, it was even difficult to determine those conditions that were healthful. Until Pasteur's germ theory won out at the end of the nineteenth century, sea bathing, mineral waters, "fresh-air cures," and sunshine—the latter being particularly for the romantic wasting away that was tuberculosis—were among the many cures and nostrums that were briefly but seriously adopted.

In the case of cataclysmic events, such as fire or lightning, the owners or occupants of buildings could do little to prevent their occurrence. Lightning most often caused fires, and fires and structural failures threatened owners' investments in buildings. With the development of insurance this fact could be viewed as little more than an individual's wager on the likelihood of the problem arising, but from medieval times it had been recognized that this gamble also risked the safety of other structures and the people in them. Since there were no certainties involved, the process of regulation moved slowly, accelerated by catastrophes and slowed by the objections of influential owners of buildings.

The provision of comfort required the insertion of tubes, wires, fixtures, and equipment into the fabric of

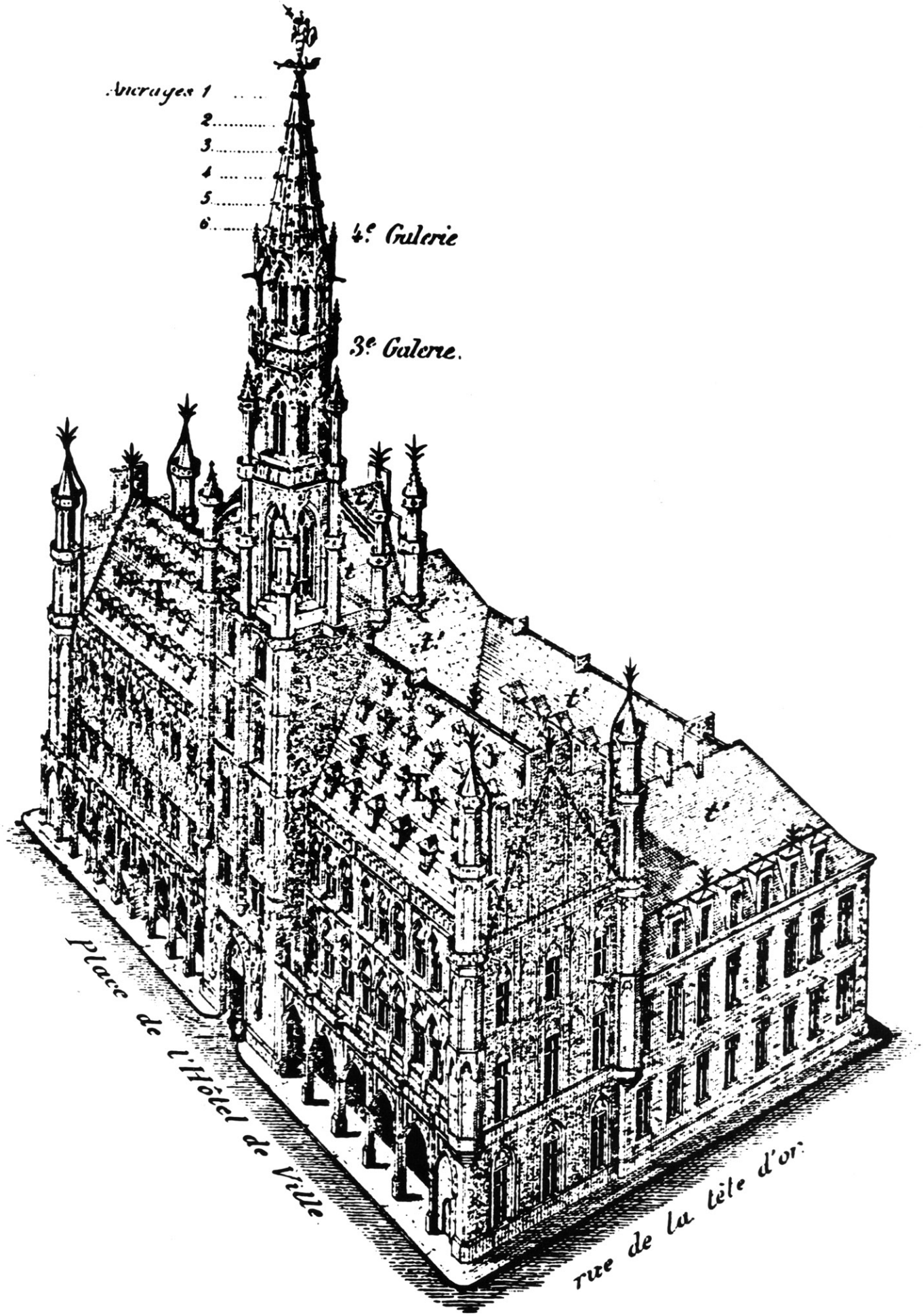
buildings. This work became increasingly specialized as time went by, until each type of system developed its own engineers, draftsmen, and contractors. No longer were the "natural philosophers" and toolmakers of the eighteenth century capable of applying their general knowledge of scientific principles to a variety of tasks, and tests and measurements were developed to provide more exact consideration of the systems involved. These provided much of the information on which standards and regulations were based.

Still, these systems (except for elevators, which demanded visibility) were largely unseen and certainly not displayed. Architectural styles of the eighteenth and nineteenth centuries were on the whole committed to presenting an illusion of the past, or at least a recognizable evocation of historical forms. Sir Charles Barry's Reform Club in London (1840) prompted the French critic César Daly to write:

> [It is] almost a living body, with its complex circulation systems; for in its walls which appear as immobile, there circulate gases, vapors, and fluids through the hidden ducts and wires. These latter constitute the arteries, veins and nerves of a new organized being, heat is conveyed by them in winter, fresh air in summer, and in every season they supply light, hot and cold water, food, and all those numerous accessories which an advanced civilization requires.[1]

While Daly admired the systems within the Reform Club's building, he seems to have been equally impressed by the cunning with which they were concealed. Architectural revivalism, particularly in the late nineteenth century when buildings' dimensions did not always allow precise historicism, left sufficient latitude to accommodate the necessary elements of comfort and convenience. Although fireplaces were included in many of the new tall commercial buildings, they were at one time recommended for ventilation purposes and often might not be at all suited for burning a fire. Lighting, long principally a transportable piece of equipment, had its system embedded in the fabric of the building, but the actual lamps were visible imitation of the lamps of the past.

When Le Corbusier in 1923 wrote "a house is a machine for living in," he not only proclaimed an esthetic principle, but at the same time recognized a fact regarding all buildings of that time. Wires and pipes might be hidden, but lamps, switches, grilles, and steam radiators were visible. By the middle of the twentieth century the systems within a building might account for a quarter or even half of its total cost. The function of architecture had acquired an increasing responsibility for the ease and well-being of the buildings' occupants.



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8 Lightning Protection

1752 Lightning rod described in Benjamin Franklin's *Poor Richard's (Improved) Almanac*

1754 Prokop Divis erects a lightning tower in his Czech village

1755 Boston earthquake blamed on the use of lightning rods

1777 George III overrides the advice of Franklin and the Royal Society for protecting the Purfleet magazines

1782 Robespierre defends a French advocate of lightning rods against his neighbors' complaints

1823 Académie des Sciences supports J. A. C. Charles's "double cone" of lightning protection

In ancient times it was believed that sleeping bodies were protected from lightning because in a relaxed state they offered no resistance to it, and obeying another myth at least one Roman emperor donned a wreath of laurel whenever a storm threatened.[1] On the whole, the most popular explanations of lightning and defenses against it were based on the assumption that it was divinely instigated and directed. It became a custom to ring church bells in order to dissipate the force of lightning, but there remained a theological embarrassment in the frequency with which the tall towers of churches were struck and demolished by bolts of lightning.

Peasant practices regarding protection from lightning often related to the bonfires built in some parts of Europe for the midsummer celebration of the Eve of St. John. Brands from the bonfire, when taken home and carefully stored in a cupboard, were believed in one district to protect the house from "lightning, conflagration, and certain maladies and spells."[2] In other locales, defense against lightning was provided by children throwing garlands of flowers on the cottage roof or by a householder's hanging on a wall a bunch of mountain arnica, an herb to which medicinal qualities were also attributed. A surer protection in some areas was said to lie in the fact that lightning would never strike a house in which a crossbill finch was kept in a cage.[3]

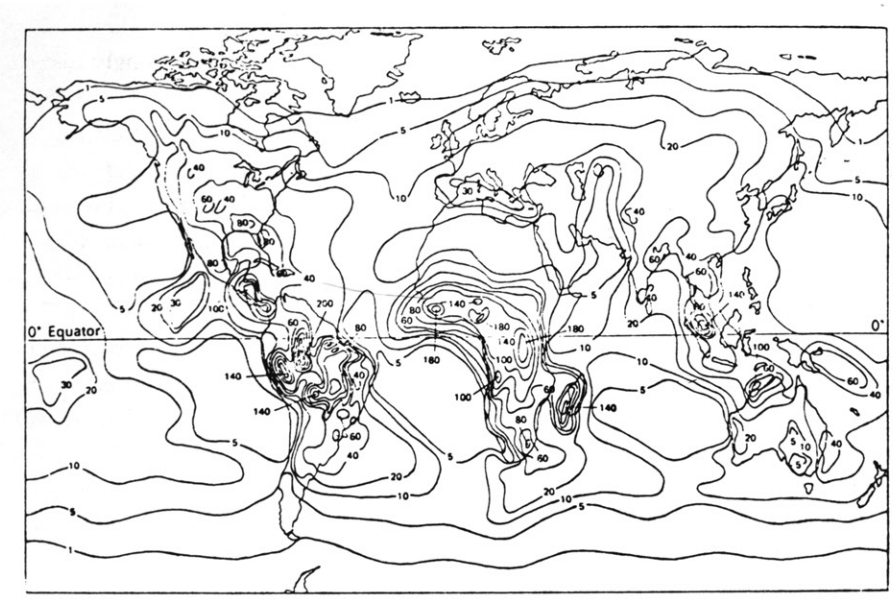
Churches and army powder magazines seem particularly to have focused public and official attention on the use of lightning rods. These subjects were combined when in 1767 lightning struck a church in Venice where city authorities had stored 100 tons of gunpowder in vaults they assumed to be protected by divine authority. A large area surrounding the church was razed and many were killed in the explosion.[4] There were bitter arguments between faith and science, but during the lifetime of Benjamin Franklin lightning rods were mounted on many of the major churches in Europe and in countries elsewhere.

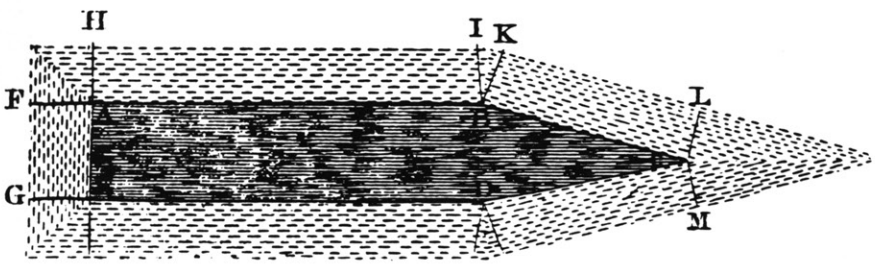
No other name is so strongly associated with lightning protection as Franklin's. His interest in electrical experimentation began at a demonstration presented in Boston by Dr. Archibald Spencer, a Scotsman who started his career as a male midwife, ended as a preacher, and at a time between those occupations lectured on electricity. A year later Spencer played an engagement in Philadelphia and sold all of his demonstration equipment to Franklin. In the meantime one of Franklin's English friends sent the Library Company of Philadelphia an "electric tube" in which could be stored the electrical charge produced by friction, along with pamphlets on European experiments with electricity and his own instructions. The gift was well-timed. At the end of 1748 Franklin retired from his printing business and had "no other tasks than such as I shall like to give myself and of enjoying what I look upon as a great happiness: leisure to read, study, make experiments, and converse at large."[5] Within six months of his retirement Franklin had conducted a sufficient number of experiments to write of them to Peter Collison and others of his many correspondents. The circle of Franklin's friends, the "Junto" organized in 1727 and later renamed the American Philosophical Society, provided both collaborators and an enthusiastic audience for demonstrations of the mysterious workings of electricity.

One of Franklin's early findings was that sharp-pointed conductors drew off electrical charges far more

8.1 The frequency of thunderstorm days varies as indicated by this map, developed from information of the World Meteorological Organization. The need for lightning protection depends also on the intensity of the thunderstorms that may occur. (G. P. McKinnon, *Fire Protection Handbook*, 1976. Reprinted with permission. Copyright 1986 National Fire Protection Association, Quincy, Massachusetts.)

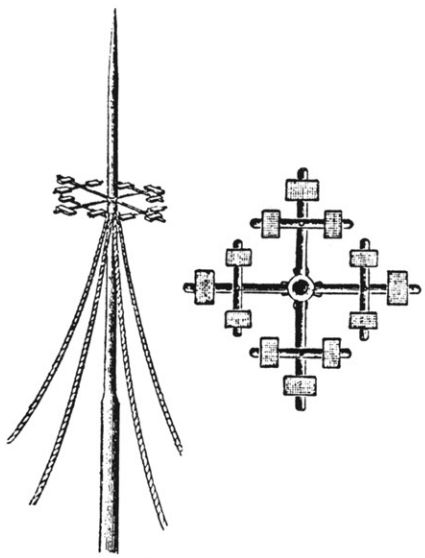
8.2 Franklin explained his theory of points in a paper he published in 1749. Small dashes indicate the charge ("electrical atmosphere") around the metal shape. In Franklin's words, at the point "the quantity is largest, and the surface to attract and keep it back the least," and therefore "you can get it away still more easily." (*Journal of the Franklin Institute*, April 1906.)





readily than blunt-ended ones (fig. 8.2). Since Franklin had concluded that lightning was much the same as the sparks that leaped between points in his experimental paraphernalia, he hungered to conduct experiments with thunderclouds overhead. He proposed to place "a kind of sentry-box" on a high tower with a pointed iron rod extending 20 or 30 feet into the air. Inside the sentry box a man would stand on a cake of wax to provide insulation and would hold a wire with which sparks could be drawn from the iron rod. But in Philadelphia there were no steeples or spires that offered sufficient height, and the famous kite trick, the "Philadelphia experiment," was devised:

> To the top of the upright stick of the [kite] cross is to be fixed a very sharp pointed wire, rising a foot or more above the wood. . . . As soon as any of the thunder clouds come over the kite, the pointed wire will draw the electric fire from them. . . . And when the rain has wet the kite and twine . . . you will find it streams out plentifully from the key on the approach of your knuckle.[6]



8.3 The "weather machine" of Prokop Divis had boxes of needles on all four branches, providing a multitude of points. It was mounted on a wooden shaft, but chains also connected it with the earth. (*Popular Science Monthly*, January 1893.)

This experiment led to Franklin's invention of the lightning rod. Scholars, as is their inclination, have questioned whether Franklin's kite experiment preceded his invention of the lightning rod. In fact, some doubt that he performed the experiment.

In September 1752, Franklin attached to his house an iron rod with two bells attached. The rod's purpose was experimental and the bells' ringing informed him when a charge had been accumulated for his use. Within a month of this project, there was published in *Poor Richard's (Improved) Almanac* a description of the means by which buildings could be protected from damage by lightning. Written by Franklin under the pseudonym of Richard Saunders, the instructions are simple:

> Provide a small Iron Rod . . . but of such a Length that one End being three or four Feet in the moist Ground the other may be six or eight Feet above the Highest part of the Building. To the upper End of the Rod fasten about a Foot of Brass Wire, the size of a common Knitting-needle, sharpened to a fine Point; the Rod may be secured to the House by a few small Staples. If the House or Barn be long, there may be a Rod and Point at each End, and a middling Wire along the Ridge from one to the other. A House thus furnished will not be damaged by Lightning, it being attracted by the Points and passing thro the Metal into the Ground without hurting any Thing.[7]

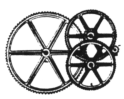
By 1755, a Boston minister could complain that there were "more [lightning rods] erected [here] than any where else in New England" (he blamed the lightning rods for overcharging the earth with electricity and thereby causing a recent earthquake in the city).[8]

There is at least one other person sometimes given credit for the invention of the lightning rod. Prokop Divis was a priest in Czechoslovakia, where in 1736 he was appointed pastor in Primetice, a village in southern Moravia.[9] Although relatively isolated, Divis kept in touch with scientific progress through visits to the region's seats of learning, reading published reports, and correspondence. The duties of his parish appear to have required little of Divis's attention, and he devoted much of his time to experimentation.

After a preliminary study of electrical phenomena, Divis focused his thought on atmospheric charges of electricity. In 1753 he wrote an explanation of why a Russian physicist had been killed while conducting experiments with lightning. A copy of this paper was sent to Leonhard Euler, president of the Berlin Academy of Sciences, and in his letter Divis implied his intention to construct a device that would diminish the threat

of lightning over a relatively large area. In June of the following year this conductor was erected in a garden plot near Divis's rectory. Convinced that lightning was an electrical discharge and that metal points would attract it, he designed a lightning rod that bore a multitude of points (fig. 8.3). The central rod was supported by a wooden upright 48 feet high at first, and later said to have been increased to 132 feet, which was guyed with iron chains. At its top the iron rod bore two crossbars, each end of them having a smaller crossbar. In this way the rods provided 13 points, though blunt, but in addition each of the 12 horizontal points held a box filled with iron filings in which 27 brass needles stood erect. If one ignored the ends of the rods as points, there were altogether 324 brass needles to attract electrical charges.

For two years Divis experimented with his lightning rod. He proposed to his government the location of similar towers throughout the kingdom, but ranking scientists squelched the plan. The summer of 1756 was extremely dry in Moravia, and the farmers around Primetice blamed Divis's lightning rod with drawing off the moisture of clouds as well as their electrical charge. Anger grew and a throng of farmers tore down the tower.

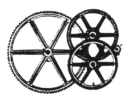


In France, too, experimentation and controversy thrived. According to a description of Paris published in Amsterdam during 1782, lightning rods were rarer in the capital city than in large provincial towns.[10] Abbé Bertholon, a priest of the Lazarist order and a professor of experimental physics, had installed lightning rods in Lyons, his native city, and in other parts of southern France. Bertholon was a friend of Benjamin Franklin and followed his principles, except for the French inclination to count height as the paramount consideration in the design of lightning rods. In Paris a *paratonnerre* 185 feet high was installed at the Hôtel de Châtost in Faubourg Saint-Honoré, its lower end extending 28 feet below ground level into the water of a well. On the other side of Paris, a convent had a rod 3 feet higher that went 90 feet into the ground.

Elsewhere in France, M. de Vissery de Bois-Vale, a retired lawyer, was an amateur experimenter who dabbled in the scientific paraphernalia that fascinated so many gentlemen of that period. He corresponded with other experimenters, including Franklin. A few months after he wrote Franklin in 1782, Vissery put a lightning rod of his own devising on his house at Saint-Omer.[11] Neighbors gawked and gossiped, soon reaching the conclusion that the apparatus might attract bolts of lightning and thus endanger their own properties and families. They were deaf to Vissery's explanations. When his neighbors took their complaints to the sheriff, Vissery's theories failed to sway that official, and an order was issued to force removal of the lightning rod.

In defense of scientific truth, the amateur appealed to the Council of Artois, which sat in the regional capitol. Vissery's lawyer gathered scientific opinions from France's most famous experts, including Abbé Bertholon. It was at that time customary for established lawyers to prepare the substance of a case, but assign its oratorical presentation to someone younger. The lawyer chosen to argue M. Vissery's case was Maximilien F. M. I. de Robespierre, ten years

later to mastermind the Reign of Terror before he was himself guillotined. When offered the case, Robespierre had been a member of the bar for only two years, and the case of Vissery provided a rare opportunity to advance his career at a time when legal oratory was inclined to lead to political oratory. Using the older lawyer's compilation of theories and opinions, young Robespierre began his argument by speaking of Galileo and others who had been oppressed because of their unpopular scientific views. He went on to review the electrical principles known at that time—although his own scientific education was negligible—and summarized the short history of lightning rods. He closed by invoking royal support through a description of several electrical experiments that Louis XVI himself had caused to be conducted. "If there were any doubts about the effects of these devices, the scientists involved would never have experimented on such a dear and such a sacred head." At Robespierre's request Vissery financed the publication of the speech, and Robespierre sent copies to friends, associates, charming young ladies, and even Benjamin Franklin.[12]

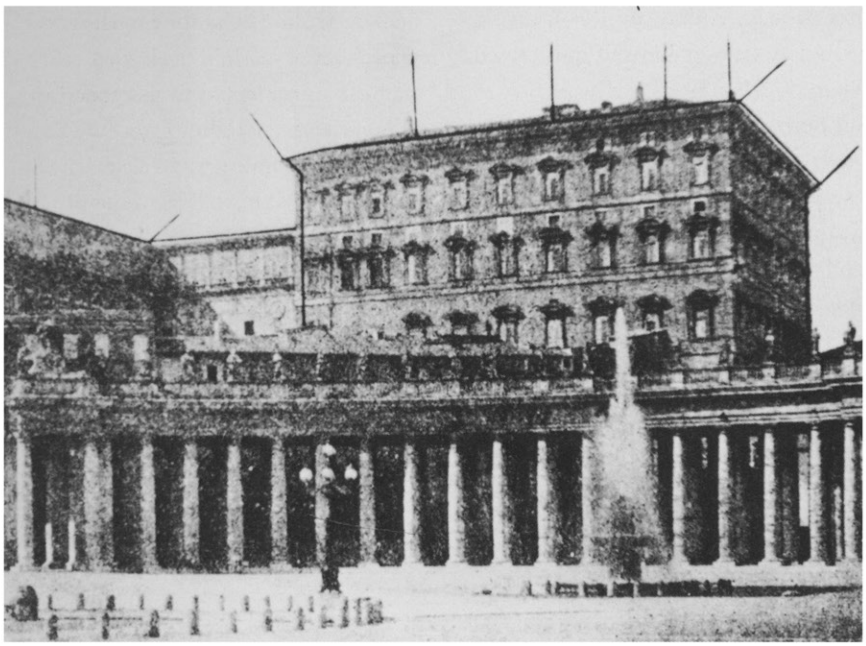


Franklin's first statement on lightning as a form of electricity had been presented to the British Royal Society of Arts in 1750 by John Mitchell, physician, cartographer of the American colonies, and a member of the Society. Although Franklin's *Autobiography* reports that the paper "was laught at by the Connoisseurs," it was published and attracted the attention of scientists. Three years later the Society awarded Franklin the Sir Godfrey Copley Gold Medal for his electrical experiments, and after another three years he was elected to membership. When the dean and chapter of St. Paul's Cathedral in 1769 asked the Royal Society for advice on lightning protection for the church's dome and cupola, it was Franklin who advised them regarding the placement of rods, points, and wires. In 1772 the Board of Ordnance consulted Franklin, who was once more in England, about protection of its principal installation of powder magazines at Purfleet. He visited the location and recommended that pointed lightning rods be installed. The problem was then taken to the Royal Society, which appointed a committee. The members of that committee agreed with Franklin that pointed rods should be placed on the magazines, and it was he that wrote their final report.

There was one dissent among the five members of the committee. Benjamin Wilson, an experimenter and writer on electricity, was also a painter and had completed a portrait of Franklin about a dozen years before. It was Wilson's contention that pointed rods would attract lightning to the magazines, causing a greater likelihood of damage than would result from blunt rods. Wilson published pamphlets that angrily presented his argument.

Years later, after the American Revolution had begun, lightning struck at Purfleet, although none of the magazines was damaged. The controversy was then revived with George III avidly supporting Wilson's point of view and patriotic undercurrents strongly influencing opinion. The king ordered blunt-ended conductors placed on the Purfleet magazines and the royal palace. The Royal Society was thus placed on the defensive, since George III had publicly contradicted its scientific advice.[13] The

8.4 The Continental method of protecting buildings at the start of this century required tall vertical rods spaced about the roof. At corners the rods were usually projected at an angle of about 60°. This installation at the Vatican used iron rods instead of copper, apparently seeking to lower the cost of protecting over seven acres of buildings. (K. Hedges, *Modern Lightning Conductors*, 1905.)



president of the Society, Sir John Pringle, court physician but for more than 20 years a close friend of Franklin, refused to be persuaded that blunt ends were superior because of royal preference, and in the end he resigned the presidency of the Royal Society.

Lightning protection had come to be accepted, but not without a residue of doubt. Sir William Thomson, later Lord Kelvin, commented, "If I urge Glasgow manufacturers to put up lightning rods they say it is cheaper to insure than to do so."[14] This attitude was not peculiar to frugal Scots, for many articles on lightning rods published in the late nineteenth century advised that the cost of rods and conductors should be carefully compared with insurance premiums. At the same time, insurance companies sometimes assumed a portion of the cost of placing rods on buildings for which they held policies. Some German companies paid a small percentage of the cost, but the East Prussian Fire Insurance Company bore half the cost for its customers.[15] Other companies reduced premiums for protected property. In Schleswig-Holstein some fire insurance companies reduced their rates on houses roofed with slate or tile by 5 percent if lightning rods were installed, and they lowered rates on thatched houses and windmills by 20 percent.

Another debate about lightning protection occurred in the mid-nineteenth century between two prominent British scientists. Michael Faraday had a long and distinguished record in electrochemical experimentation when he was asked in 1853 to propose the proper protection for Eddystone Lighthouse, perched on a rock outside Plymouth harbor. Faraday's opponent, William Snow Harris, had begun his study of lightning in 1822 by proposing that rods and conductors be installed on British navy vessels. The subject continued to hold his attention, and in the 1850s Harris was recommended by the architect, Sir Charles Barry, to provide a protective system for the new Houses of Parliament.

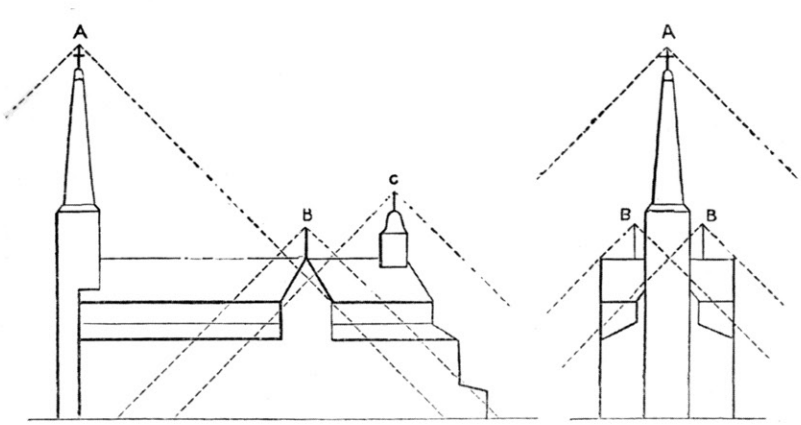
The Faraday-Harris controversy centered on the form of conductors that should be employed in an installation of lightning rods. Faraday viewed them as electrical conductors and insisted that their cross-sectional

area determined the degree of protection that they afforded. Harris considered as critical the amount of conductor surface along which a streak of lightning might travel to the ground, and he employed metal ribbons or hollow tubes in which the extent of surface was very great in relation to the amount of metal. Years later a British admiral recalled the vehemence of the two scientists: "Each told me that the other 'knew nothing about it.' "[16] In 1892 Oliver Lodge, then the ranking British expert on lightning, concluded that Harris was correct in placing primary value on the surface area of conductors, but in the 1970s the lightning protection regulations of several countries (Australia, Germany, Great Britain, and the United States) made no distinction among strips, rods, and wire cables as conductors.

Although Franklin has assumed that his points attracted lightning, others portrayed their action as that of effectively shielding a specific area. J. A. C. Charles, a French physicist, proposed that each lightning rod be considered as protecting everything within a cone having its point at the tip of the rod and its base a circle with a radius twice the height of the rod, hence the "double cone of Charles." The conical shape was suggested by observations that lightning often approached grounded objects in an upward movement. Thus, if one could define an area of protection, it seemed reasonable that it would be generally conical, although the exact proportions were an arbitrary assumption (fig. 8.5).

If lightning rods were to be effectively placed for protecting the towers of cathedrals and chimneys of mansions, some geometric principle seemed necessary to guide their placement, a principle much more specific than Franklin's speaking of his points attracting the electrical charge of clouds. One of the first rules accepted was the "double cone of Charles," which the French Académie des Sciences espoused in 1823.[17] A "single cone" with its base's radius equal to the height was theorized by Joseph Louis Gay-Lussac, professor of physics at the Sorbonne. As the notion of cones of protection came to be more firmly implanted, other proportions were proposed. The steepest form considered through the years was a cone with its radius half its height, and there were unusual variations in which the slope of the cone's sides was a concave curve or the zone of protection was cylindrical. In 1854 a French committee, formed to assess the current knowledge of lightning protection, firmly stated that cones of space should not be considered as describing the extent of protection by lightning rods, and through the remainder of the nineteenth century this admonition was repeated by other committees and several individual scientists. Nevertheless, in lieu of any other specific rules that could be used to determine the placement of points, the notion of cones of protection has persisted.[18]

The French Ministry of the Interior in 1822 had ordered that lightning protection be provided for all public buildings, and the following year a distinguished committee of the Acadé-



8.5 Although different experts and various national agencies recommended other proportions, English military authorities and most English practitioners employed a cone of lightning protection with its height equal to the radius of the base, a 45° slope on the side. Rods were placed so that such cones enveloped the entire form of the structure. (G. J. Symonds, *Lightning Rod Conference*, 1882.)

mie des Sciences presented its recommendations. From large buildings an iron rod should extend upward 23 to 30 feet, they said, including a top 22 inches of copper point, either gilded at the end or tipped with a bit of platinum. An iron rod, held away from roofs and walls by brackets, should extend to the ground, where it could be taken to a well or a pit filled with charcoal. The "double cone" of protection was favored by the committee, but the "single cone" was accepted for installation on church towers. The committee strongly urged that all metal on the surface of a building—gutters, tie rods, or roof coverings—be connected to the system, so that such metal would not divert lightning from the conductor's path.

At midcentury there began a succession of French committees charged with the study of lightning protection. As a beginning, the committee in 1854 supported the recommendations of 30 years before but pointed out two new considerations. First, because of an inquiry made by the company building the Palais d'Industrie for the next year's exposition, the problem of metal-framed buildings was approached. With the construction of great glass and iron buildings for international fairs and railroad stations, the building itself became a conductor. The question could have raised doubts about the wisdom of constructing metal buildings, but the committee considered lightning rods imperative on metal buildings and required that they be connected to the building's frame.[19] Second, with regard to new additions to the Louvre, the committee stressed that if conductors could not be extended into a well they should have two branches, one extending into the earth to reach a stable level of moisture and the other kept near the ground, where surface moisture from a thundershower might provide a ground.

A subsequent French committee in 1867 gave much of its attention to the placement of rods on powder magazines, because the year before several French magazines had been struck by lightning although provided with lightning rods. At the same time the committee reduced the recommended height of rods by 13 feet, thus lowering the high rods that had long been the earmark of French installations.

If the principles of lightning protection were debatable among scientists, they were even more bewildering to ordinary citizens. Lightning rod salesmen became the equal of patent medicine hawkers in the United States, and the stories of their trickery multiplied. Mark Twain in 1870 wrote of being persuaded by a glib peddler to install lightning rods on his house and being sold a much greater number of rods than was needed and "3,211 feet of the best quality zinc-plated spiral-twist" conductor wire.[20] Twain's hyperbole was deserved by the fly-by-night door-to-door salesmen who bilked householders, and the genuine danger was inflated by an endless store of tales about buildings and trees having been wrenched apart by bolts of lightning and balls of fire blazing erratic paths through bedrooms while the occupants cowered in bed. Like patent medicines, the sale of lightning rods was very much a trade based on fear and fabrication.

In 1875 a brilliant Scottish scientist, James Clerk Maxwell, proposed a variation on the usual methods of lightning protection, which assumed that rods should gather electrical charges from the sky and drain them into the ground (fig. 8.6). Experiments almost a century before had shown that there was no electrostatic charge in the center of a hollow conductor,

and on that basis Maxwell proposed the "bird cage" method of protecting buildings from lightning. He recommended an enveloping network of conductors, with connecting rods on the top of a building, leading to the ground in several directions, and connecting conductors all around the base of the building. The Germans to some extent adopted this idea for a period, but one British expert shrugged, "It would be unpleasant, when you reached home out of a storm, to find it so highly charged as to knock you down directly as you tried to go in."[21]

Protecting the splendid Gothic town hall of Brussels became a preoccupation of Professor L. H. F. Melsens, a Belgian physicist and chemist. His system for that building was begun in 1865, and some believed it the best protected building in the world. The town hall's tall tower was particularly susceptible to lightning discharges, so eight conductors led from it to the ground.[22] Melsens did not use the tall rods favored by the French (figs. 8.7, 8.8). Instead he installed 37 "point arrangements," some of which included several pointed short rods plus *aigrettes*, which were made of eight wires fanned out.[23] Beyond any scientific basis, this method had the distinct advantage of not seeming to clutter the intricate ornamentation of the tower. In spite of such elaborate precautions, in 1888 the town hall was struck by lightning and set on fire. After the roof was examined it was concluded that a horizontal bar of metal had not been connected to Melsens's network, and from it sparks had ignited gas.

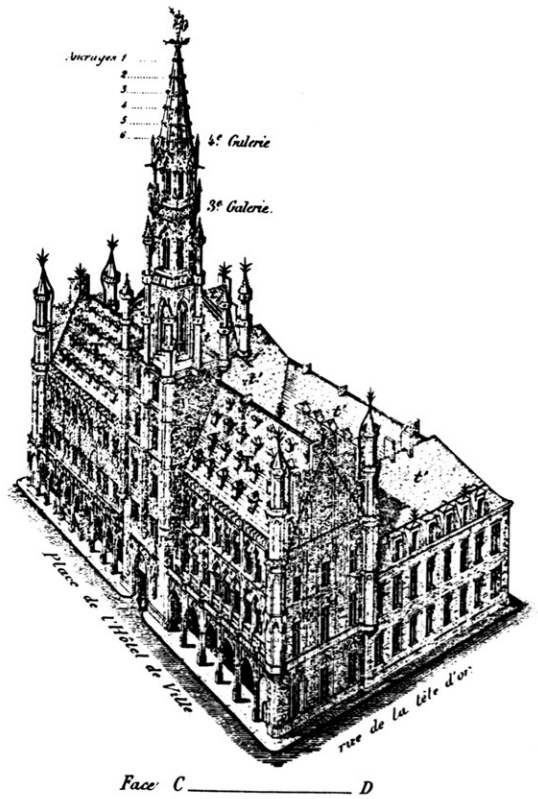
If Lord Kelvin had difficulty persuading Glasgow investors to provide lightning protection for their buildings, greater economic resistance was to come. Reports of governmental committees represented the views of respected scientists and consequently became the principal basis for regulations issued by city governments, governmental agencies, and the military forces. Such rules were necessarily written in a general manner, intended to provide sound protection for all buildings, in spite of the extreme variety of sites and forms that the structures included. At the end of the nineteenth century, a German building official pointed out that if all buildings were protected according to such regulations, the cost of installing the rods and conductors would be greater than the cost of damage that could normally be expected from lightning.

Discussions of lightning protection at the turn of the century increasingly focused on rural structures. An early statistical report on an area of central Germany concluded that the danger from lightning was nearly four times as great in the country as it was in urban areas.[24] The case was best stated in a 1901 study of lightning fatalities in the United States.

8.6 The founder of electromagnetic theory, James Clerk Maxwell, designed a system of lightning protection that did not make use of metal rods jutting into the sky. Instead, conductors (shown here by dashed lines) ran along the edges and corners of the structure. The system was usually referred to as being like bird cages or the wire meat safes of that day. (O. J. Lodge, *Lightning Conductors and Lightning Guards*, 1892.)

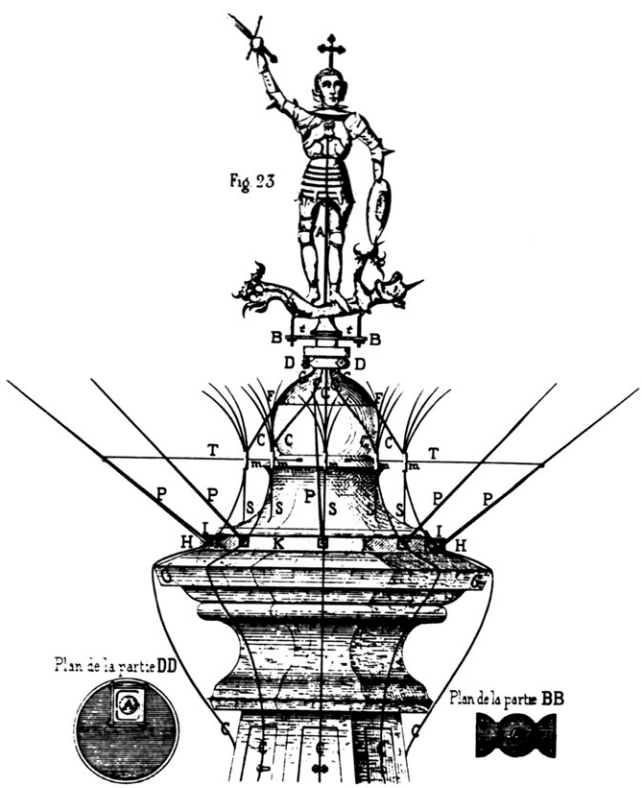
8.7 Professor Melsens's treatment of the Hôtel de Ville, Brussels, set *aigrettes* of metal points around the figure at the top of the tower, on each of the turrets, and at the gables of the building's many dormers. (L. H. F. Melsens, *Des Paratonnerres*, 1877.)

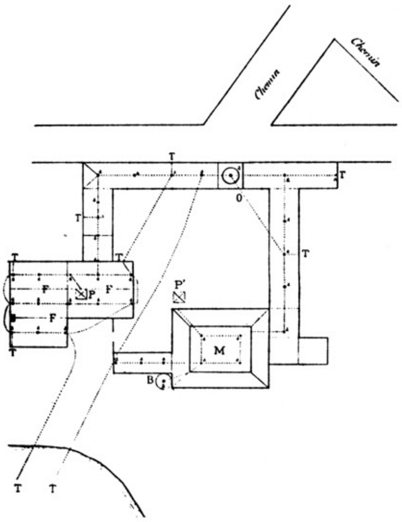
It is not surprising that so few lightning strokes fall in the cities. The modern city building, with its metallic roof and steel frame, is a fairly good conductor of electricity, and is in much less danger of receiving a damaging stroke of lightning than an isolated dwelling in the open country. The multiplication of telegraph, telephone, and electric light wires in cities also adds to the effectiveness of silent discharges in relieving the electrical tension during a thunderstorm; but should a cloud with a tremendous store of energy quickly approach, all the wires in ten cities would not prevent it from discharging right and left until its store of energy had been dissipated.[25]



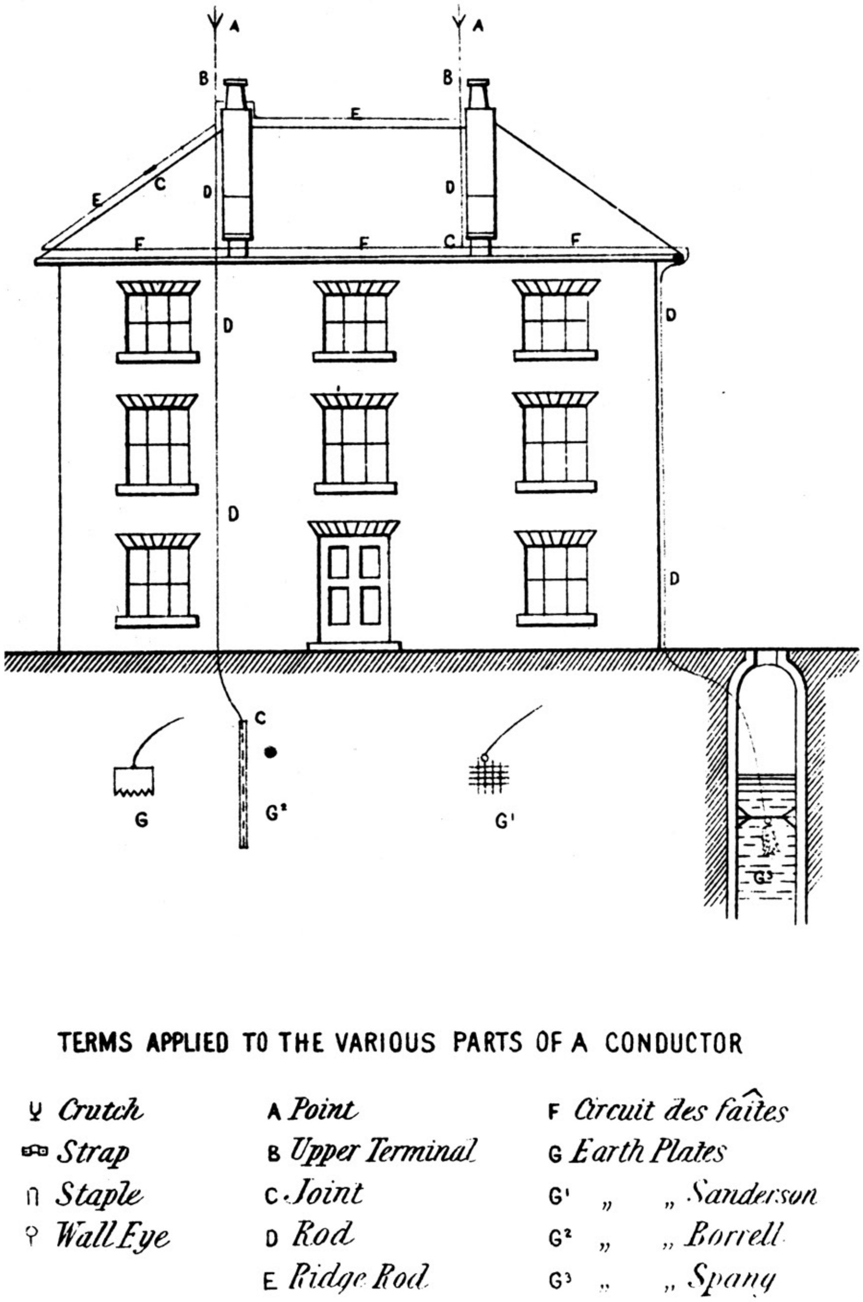
Spires, towers, smokestacks, water towers, and skyscrapers might certainly be subject to lightning even in the densest urban environment, but at the same time they could serve as protection for lower structures.

Skyscrapers were a new problem. Towers and chimneys in the midst of cities had often been damaged by lightning. How would the tall steel-framed buildings survive? By 1902 it was reported that in the United States the quality of lightning rod installation had so greatly and generally deteriorated that architects were dropping that portion from their specifications for new construction. Hence, many of the finest and highest buildings in the centers of cities were without protection. With insurance policies covering any loss, financial risk was lessened.[26] It was the conclusion of Britain's 1905 Lightning Research Committee that steel-framed buildings provided themselves with a high degree of protection, much like the "bird cage" system that had been expounded by Maxwell about 30 years before. If small rods were placed about the roof and properly connected to the metal frame, the building itself would con-





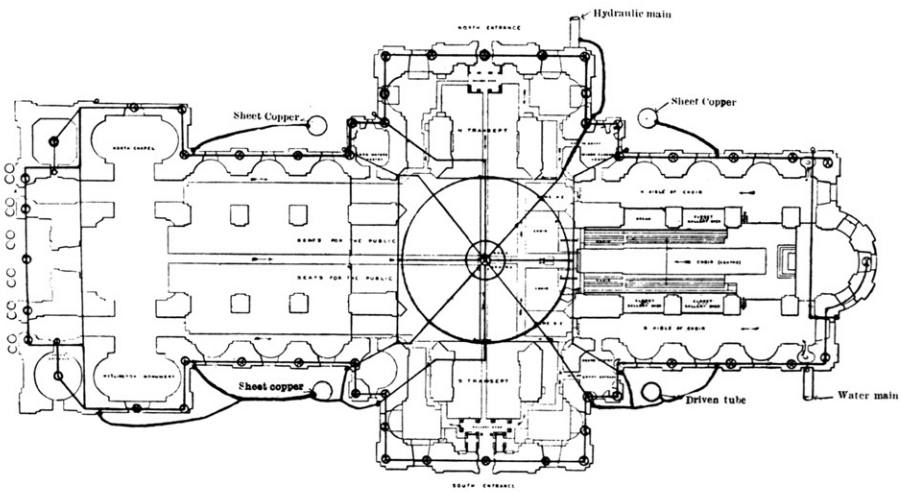
8.8 In 1882 Melsens laid out the lightning protection of a Belgian farmhouse with 37 *aigrettes* spaced along the roofs. Conductors were grounded to wells (*P, P′*) and the farm pond. (L. H. F. Melsens, *Des Paratonnerres*, 1877.)



8.9 This diagram from the 1882 report of a British Lightning Rod Conference indicates the terminology of the time. Methods shown for grounding the system (G, G^1, G^2, G^3) include most that were popular at the time, although a well was usually conceded to be best. (G. J. Symonds, *Lightning Rod Conference*, 1882.)

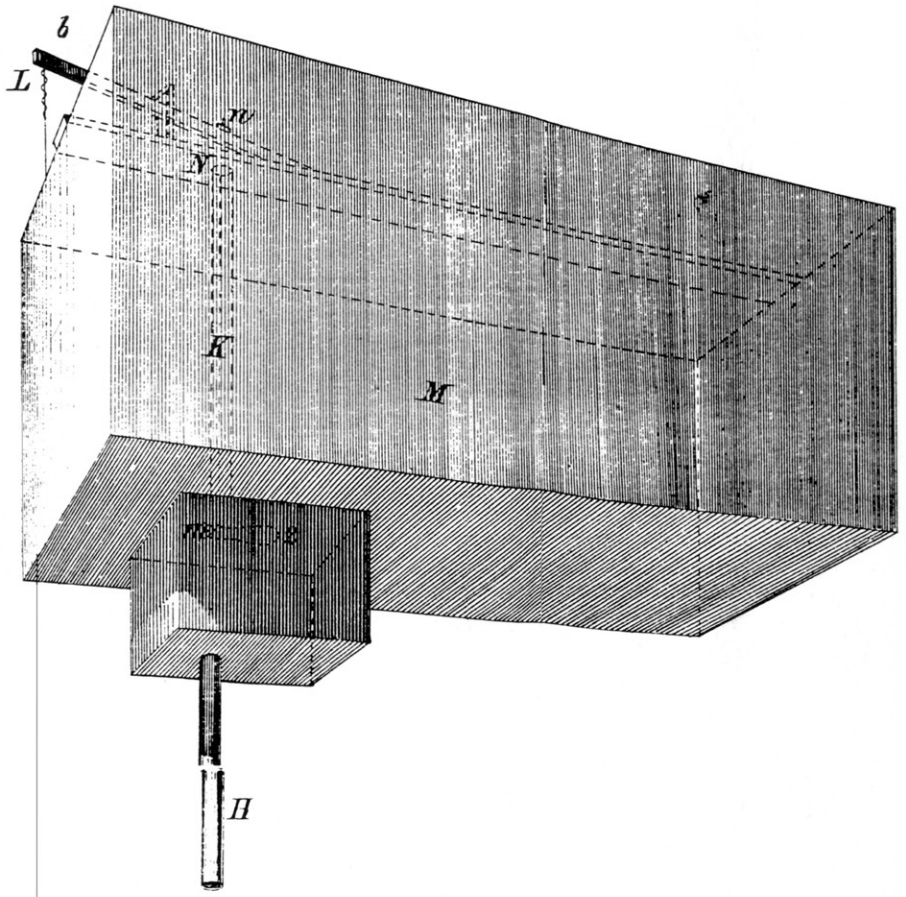
8.10 The Royal Society was consulted in 1769 about the protection of St. Paul's. Early in the present century, inspection of the cathedral found that the effectiveness of the installations that had been made through many decades was limited due to drainage, paving, and pipe-laying projects that had altered the moistness of the ground. Connections were then made to water and hydraulic mains, and many small grounds were provided by metal plates or perforated pipes buried in the earth. (K. Hedges, *Modern Lightning Conductors*, 1905).

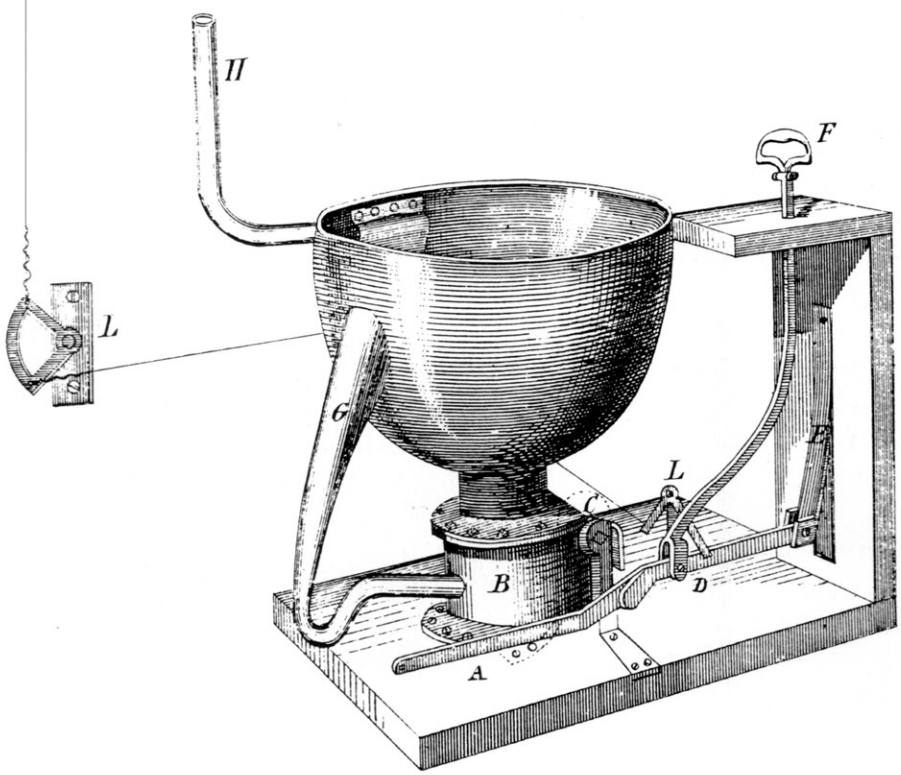
stitute a network of conductors. The principal fault found was the frequent failure to provide adequate grounding for the columns, which ended on foundations of stone or concrete without buried conductors leading to moist earth or, better yet, a deep well.[27]



Curiously enough, these same statements made in 1905 correspond to the views of the 1976 *Fire Protection Handbook* as published by the U.S. National Fire Protection Association, which also describes cones of protection in terms very much like those used in the early part of the nineteenth century.

In tall buildings the steel framework or the bars within concrete (when linked by wires or clamps) afford protection by distributing the current of lightning. But despite the tradition of cones of protection, it has been considered wise to install conductors on the walls to contend with lightning strikes against the sides of a building.[28] With the increased amount of metal within buildings, mechanical and electrical systems, it has been necessary to isolate or even shield the metal parts of interior functions from the network of lightning protection. Today lightning conductors may serve as much to defend computer installations and the information stored in them as to protect the fabric of a building.





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1596 Sir John Harington describes the water closet in *Metamorphosis of Ajax*

1775 Valve water closet patented (Britain) by Alexander Cumming, a London watchmaker

1778 Joseph Bramah patents (Britain) his improvement on the valve water closet

1860 The earth closet introduced by Henry Moule, an English clergyman

1866 New York's Metropolitan Health Law enacted following a survey of the city's sanitary conditions

Because of the remarkable engineering skill of its empire, the city of Rome in the fourth century A.D. could provide 11 public baths, 144 public latrines, 865 private baths, and some 1,352 public fountains and cisterns.[1] These were supplied with water from 13 aqueducts, and around 70 aqueducts are known to have been built in other parts of the empire. (Repairing such aqueducts was often a medieval expedient for improving a city's supply of water.) Some public latrines had flowing water beneath seats of stone or wood. Containers were placed at certain street corners, and Vespasian instituted a charge for their use and a system by which the urine collected was sold for use by fullers of cloth.[2] Within Roman houses, chamber pots were used, being usually emptied into the street. But water was plentiful, and drainage was well provided in most Roman cities. All of these advantages declined with the empire.

As late as the middle of the seventeenth century even the nobility of England were little concerned with sanitation. After the court of Charles II visited Oxford to escape the plague, a local diarist wrote: "Though they were neat and gay in their apparell, yet they were very nasty and beastly, leaving at their departure their excrements in every corner, in chimneys, studies, cole houses, cellers. Rude, rough, whoremongers; vaine, empty, careless."[3] Medieval traditions had made city streets almost as much sewers as thoroughfares. With drainage in the middle of the paving, the pedestrian was forced at night to choose between walking in filth or passing within the reach of any thieves who might lurk in dark doorways. In Edinburgh the danger of having a chamber pot emptied over one was only slightly diminished by the custom of householders shouting "Gardy-loo" from upper-story windows a moment before hurling sewage into the street.[4] From the street such ordure drained into streams and was swept to the sea and the cities downstream. Englishmen on their Grand Tour complained that garments laundered in Rome stank forever of the Tiber's waters; just as some German visitors to London claimed that clothing washed in water from the Thames never lost traces of that river's sickening stench.[5] Visitors to Paris claimed they could smell the city's filth two miles outside its gates, and fastidious Parisians who ventured into the streets in the time of Louis XIV covered their noses with hands in perfumed gloves.[6] In smaller towns the problems were much the same. Viollet-le-Duc mentions that in towns of central France a stream through the center would customarily be called *merderel*, named for its foul contents.

Castles and monasteries often had privies projecting over their moats or streams. Built within towers or buttresses, these "garderobes" (wardrobe being a euphemism) emptied through shafts hollowed in the masonry. Where there was neither stream nor moat, cesspits were dug. Additional comfort was provided its users when the garderobe was warmed by being built into the masonry mass of a fireplace. For defecation peasants had the custom of retiring to a distance "a bow's shot" away from their dwellings. At the country houses of well-to-do Englishmen the gardens served a similar purpose, and leaving a social gathering "to pluck a rose" was another of the numerous euphemisms, meaning either a visit to a "bog-house" at the back of the garden or a more casual solution.

Chamber pots were provided inside houses of the prosperous, and the task of emptying them ranked high in servants' complaints.[7] Still at Versailles the ceremonies of Louis XIV's daily

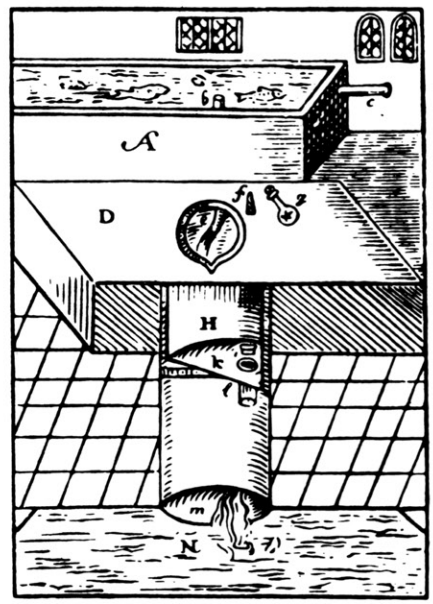
awakening included two *porte-chaise d'affaires*, attendants dressed in black velvet, who had the honor of removing the royal pot from beneath the king's *chaise-percée*. Those of noble birth or considerable wealth had such seats, ornately decorated, richly padded with velvet, and having a hole in the center of the seat cushion.

The lavish public baths of the Roman empire were not primarily intended for cleanliness. When a gong announced the daily opening of a bath, Romans, including citizens, slaves, freemen, and children, thronged there to watch sporting events, take pleasure in the luxurious decoration, hobnob with acquaintances of their own station, and perhaps bathe.[8] Smaller public baths were provided by the government or operated by private owners, and the houses and country villas of the rich were usually outfitted with a few small rooms that were the domestic bath, perhaps heated by circulating hot air beneath the stone floor as were the public baths.

Public baths continued to exist in much of Europe during the medieval period. The stews—as medieval baths, both public and private, were called—by the seventeenth century had become little more than brothels, although they were sometimes used for the steaming that might be prescribed as a cure for illnesses. Churchmen attacking the stews as centers of sin may have had some effect, but the decline of public baths was probably as much influenced by the increasing price of soap and fuel, as well as the years of plagues. Nobility continued to bathe splendidly. Tubs were hollowed out of marble for kings and dukes, although they sometimes required submerged sheets and cushions to protect royal rumps from the cold stone, a problem avoided in the wooden tubs that were used by people less grand. It is said that Louis XIV had at Versailles at least 100 bathrooms to serve the multitude of residents, visitors, and attendants, as compared with an inventory of 264 *chaise-percées*. Marie Antoinette bathed daily, but used only one tub rather than the pair considered proper, one for cleansing and one for rinsing. Except for sponge baths, the queen's subjects in Paris seldom took more than two baths per year, those during the summer and in public bathing places in the Seine. In 1800 there was not a single public bath in London and, when a lady of fashion was chided about her grimy hands, she laughingly replied, "If you think that dirty, you should see my feet!"[9]

When Queen Victoria assumed the throne in 1837 there was not a single bathroom in Buckingham Palace. For the most part, as in other houses of the wealthy, portable tubs were brought into bedrooms or dressing rooms, servants rushing up the back stairs bearing containers of hot and cool water and spreading many sheets around the tub to catch the splashing. Copper was the most desired material for making these tubs, but its expense frequently led to the substitution of tin. In simpler households a water seller might be summoned to bring a tub and the hot water required. In 1838 there were 1,013 water sellers offering that service to citizens of Paris, and there were only 2,224 tubs that were fixed in place.[10]

In 1596 the high sheriff of Somerset and a godson of Queen Elizabeth, Sir John Harington, published his design of a water closet. As a courtier, Harington had become known as a poet and man of wit, if not of impeccable taste. When he circulated about the court his translation of a salacious portion of Ariosto's *Orlando Furioso*, Elizabeth ordered him to depart from the court and before returning to translate the remainder of the poem, the literary work for which he is most remembered. Several years later Harington was again banished from court when he published *A New Discourse of a Stale Subject, Called the Metamorphosis of Ajax*. ("Ajax" is a pun on "jakes," a colloquial term for a privy.) Although filled with roguish humor and loaded with literary allusions, this and subsequent tracts on the subject give a clear description of the water closet that Harington had constructed for his country seat at Kelston near Bath (fig. 9.1)



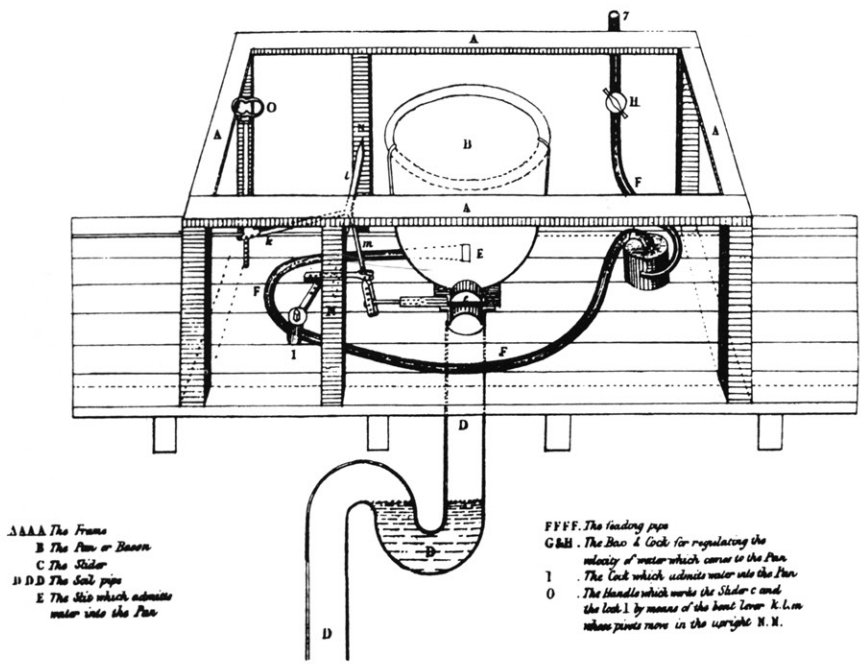
9.1 In Harington's drawing of his water closet, water cleans the bowl and an iron rod extends from the seat surface (*f*) to the stopper (*k*) beneath. If water were scarce, it was recommended that the "stool pot" (*H*) be emptied at least once a day, and after being drained it was supposed to be filled with 6 inches of water. (Fish are drawn in the tank merely to indicate that it is filled with water.) (J. Harington, *Metamorphosis of Ajax*, 1596.)

9.2 In Alexander Cumming's water closet, an upward pull on the handle (O) activated a mechanism that simultaneously moved the "slider" at the bottom of the bowl and opened a valve that allowed water to flow into the bowl. (British Patent no. 1105.)

> In the privy that annoys you, first cause a cistern, . . . to be placed either in the room or above it, from whence the water may, by a small pipe of lead of an inch be conveyed under the seat in the hinder part thereof (but quite out of sight); to which pipe you must have a cock or washer, to yield water with some pretty strength when you would let it in.
>
> Next make a vessel of an oval form . . . two feet deep, one foot broad, sixteen inches long; place this very close to your seat, like the pot of a close-stool; let the oval incline to the right hand.
>
> This vessel may be brick, stone, or lead; . . . the bottom and sides all smooth, and dressed with pitch, rosin, and wax; which will keep it from tainting with the urine.
>
> In the lowest part of the vessel which will be on the right hand, you must fasten the sluice or washer of brass, with solder or cement; the concavity, or hollow thereof, must be two inches and a half.
>
> To the washers stopple must be a stem of iron as big as a curtain rod; . . . with a strong screw at the top of it; to which you must have a hollow key with a worm to fit that screw. . . .
>
> These things thus placed, all about your vessel and elsewhere, must be passing close plastered with good lime and hair, that no air come up from the vault, but only at your sluice, which stands closed stopped; and it must be left, after it is voided, half a foot deep in clean water.[11]

A water closet of Harington's design was installed for the Queen at Richmond Palace, but this first example of the valve closet was not widely adopted and seems to have disappeared from use until almost two centuries later, when it was reinvented and introduced once again.

A British patent for a valve water closet was issued to Alexander Cumming, a London watchmaker, in 1775.

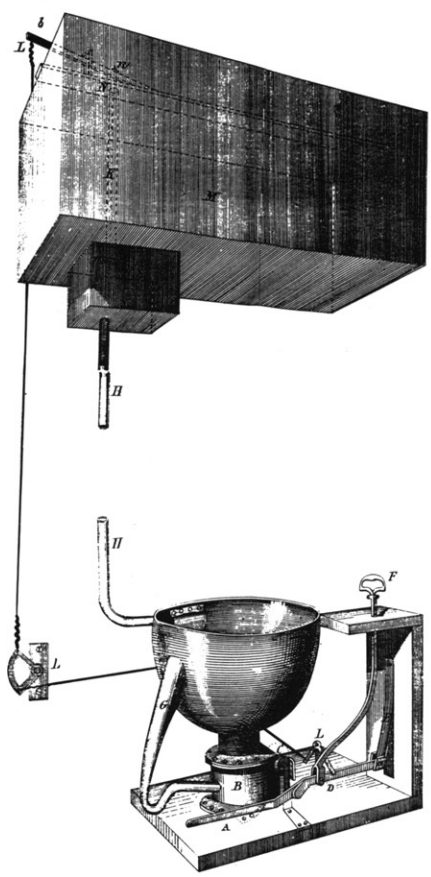


The principle was the same: a lever beside the seat operated a leather-covered valve at the bottom of the bowl, and at the same time water from an overhead tank was released through an opening in the side of the bowl.[12] Beneath the water closet itself the waste drained through the "stink-trap," an S-shaped bend in the waste pipe that retained sufficient water to seal the pipe and prevent odors entering the toilet room (fig. 9.2). Until rubber valve seals were introduced, the fit of valves quickly deteriorated, and there was little to prevent entrance of smells from the system.

Various adaptations of the basic design were developed. The most influential of these was the first patent of Joseph Bramah, a London cabinet-maker who later invented locks and many other devices (fig. 9.3). Bramah fabricated cabinets to surround valve water closets, and he turned his mind to improving the closets. Three improvements contributed to the popularity of Bramah's design, as compared to that patented by Cumming only three years before.[13] First, a metal flange was set in front of the opening through which water entered the bowl, deflecting the flow to cover much of the bowl's interior surface. Second, an overflow pipe bypassed the valve in case of stoppage. The third improvement was in the valve itself. Cumming's valve, the "slider," had moved horizontally to close or open the bottom of the bowl; Bramah's was hinged and pivoted when the lever was pulled. Thousands of such water closets were manufactured by Bramah. For about a century the Bramah valve closet was in general

use, until in 1870 the British firm of Dent and Hellyer introduced their "Optimus" improved valve closet. Almost a hundred years later this model was much like Bramah's design, except for its having a flushing rim and improved mechanics that quieted its noise and made chain-pulling less frustrating. In alphabetical order from "Optimus A" to "Optimus P," models of this closet were produced until World War II.[14]

The pan water closet was probably introduced almost as early as eighteenth-century valve closets, and the difference between them was slight. Instead of the flat face of the valve closing the opening at the bottom of the bowl, in the pan closet a shallow metal dish was hinged beneath the opening. An 1829 British patent provided a leather ring to seal the edges of the pan against a flange of the bowl, and water in the pan further sealed against odors.[15] Leather gaskets were not usual in the many pan closets available during the middle half of the nineteenth century, but one would assume that water seals at the pan and in the "stink-trap" would have been sufficient. Nevertheless, leaks in the entire assembly of pipes and fixture often defeated the purpose of these water seals. Pan closets were widely used, but there were constant complaints about them. Even with the addition of a flushing rim around the upper edge of the bowl, the design was not considered satisfactory. A nineteenth-century plumber commented: "I consider this closet a very unsanitary piece of mechanism, and totally unfit for its intended purpose, inasmuch as in a short time the internal parts become besmeared, and consequently become offensive."[16] The pan closet persisted as a basis of negative comparison for other designs, "as bad, or worse, than the pan-closet."[17] Toward the end of the nineteenth century the pan closet was sometimes still in use in Chicago, although it was not admired:



9.3 The Bramah valve closet was operated by pulling the handle (*F*), which opened a hinged valve in the chamber (*B*) and pulled the wire (*L*) that opened a valve at the bottom of the water tank. As with all valve closets, a tight-fitting valve was needed if any water were to be retained in the bowl. (British Patent no. 1177.)

> The pan-closet of twenty-five years ago was identical with the pan-closet of today. The old pan cistern-closet was defective in structure in two particular things: First, the supply pipe to the closet bowl was far too small for a proper flush; one-half inch pipe was not sufficient. Second, the closet bowl, especially the French [round] bowl, was defective in principle. The swinging of the water around the bowl in a whirlpool-like shape was not enough to cleanse the bowl nor remove the soil from the trap, or clean the trunk of the closet or wash out the soil pipe.[18]

Not much better was the hopper closet, which dispensed with valve or pan. It consisted of the hopper, an inverted cone placed directly over the

"stink-trap," and an ineffective trickle of water that spun around the sides of the bowl. The sole advantage of the hopper closet was its extremely low price. In 1849, 18 hopper closets were shipped from New York to St. Louis for installation in the Planters' House Hotel, but a few years later the installation was improved when the hopper closets were replaced with the repugnant pan closets.[19] In general, it could be assumed that hopper closets would be provided for servants and workers, because they cost about a fifth as much as more sophisticated and efficient models. At any time every country used a variety of designs, cost being the major factor in selection. So many hopper water closets were manufactured so cheaply that an English sanitary reformer suggested abandoning use of the hopper and selling the unused earthenware cones to gardeners, who could use them to protect rhubarb from spring frosts.[20]

Although the plunger water closet was used at the same time as valve, pan, and hopper closets, few improvements in its design were patented until the latter part of the nineteenth century. The mechanism was simple, though clumsy. At the bottom of the bowl, instead of a valve or pan, there was a plunger, which, when lifted by raising a handle, opened the passage between the bowl and the trap. Some plungers were simply cylinders, but others were hollow and contained a valve that opened under pressure to prevent the bowl's overflowing. Two major problems of the plunger closet were the tendency of the plunger to make an imperfect seal, even when provided with a rubber gasket, and the fact that concealed portions of the mechanism were quickly fouled. An advantage was the quantity of water retained in the bowl, about half its capacity, and this feature was kept in many later designs of water closets.

The valve, pan, and plunger water closets had provided a bowl within which feces might fall into water and a means of conveying the feces and water into a drain in which there was a trap, but the more fastidious classes required a closet that was more sanitary, although it might also be much more expensive. The washout water closet had its outlet located at the back side of a shallow bowl. Waste and water flowed through this opening into the trap, leaving an inch or two of water in the bottom of the bowl. Its principal fault lay in the fact that the water seldom had enough force to cleanse the bowl properly and eject the wastes. A variety of designs attempted to make improvements by changes of the flushing rim and the surface of the bowl, but they were, on the whole, unsuccessful.

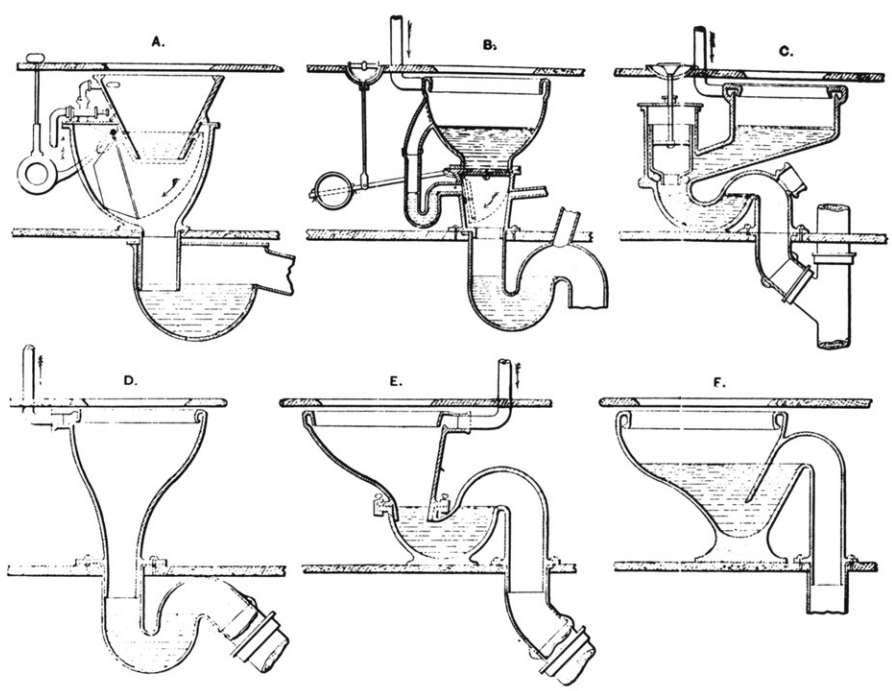
The washdown water closet was little more than a hopper closet with its S-trap at a level so high that the water in it filled much of the water-closet's bowl. A variation of the washdown closet was the siphonic closet, which used different water inlets and amounts of water to cause a siphon action with two or three sequential flushing actions.

Earlier water closets, like the other bathroom fixtures, had required cabinetwork to conceal the inelegant connections between parts made of earthenware, cast iron, and enameled iron. Makers of the ceramic portions of fixtures had long resented the fact that their portion of the final product was priced far below the pipes, traps, and valves that were made of metals. After the introduction of the flushing rim, the skill in manufacturing extremely intricate shapes of earthenware grew year by year (fig. 9.6). One of the advantages of the washout and washdown water closets was the pos-

sibility of making them from a single smooth material, earthenware, using complex shapes to replace the complicated mechanisms of earlier models. The shapes of the fixtures were made visible in bathrooms, where they shone bright and clean. Decoration could be added to their surfaces, plants and animals shaped in bas-relief and colored patterns added with sanitary glaze.

After cholera first struck England in 1831, a physician in the industrial city of Leeds began compiling studies showing that mortality rates were higher and epidemic disease spread more rapidly in the working-class areas of the city. A later investigation proved that most of those who died in London from the cholera epidemic of 1849 had drunk water from a single public pump. With repeated epidemics in Europe and the United States, cholera came to be respected as "the great sanitary inspector of nature."

Typhus, typhoid fever, and smallpox added to the death rate in nineteenth-century slums, but the frequency of children's deaths probably was largely the result of their increased susceptibility due to malnutrition. A London laboring-class family of five in 1841 is reported to have been fed for a typical week with five pounds of meat, twenty of bread, forty of potatoes, and little else.[21] Although the dispersed squalor of farmworkers' hovels was little better, the slums of large cities attracted the attention of reformers. Friedrich Engels in 1845 described *The Condition of the Working Class in England*, and 16 years later Henry Mayhew in *London Labour and the London Poor* dramatically recorded the lives of the city's impoverished. Prior to both these books, a commissioner of the English poor laws, Edwin Chadwick, published the *Report on the Sanitary Condition of the Labouring Population of Great Britain*. A hard-working and cantankerous man, Chadwick combined a massive compilation of questionnaires to physicians, police, builders, and others with the tabulation and mapping of the vital

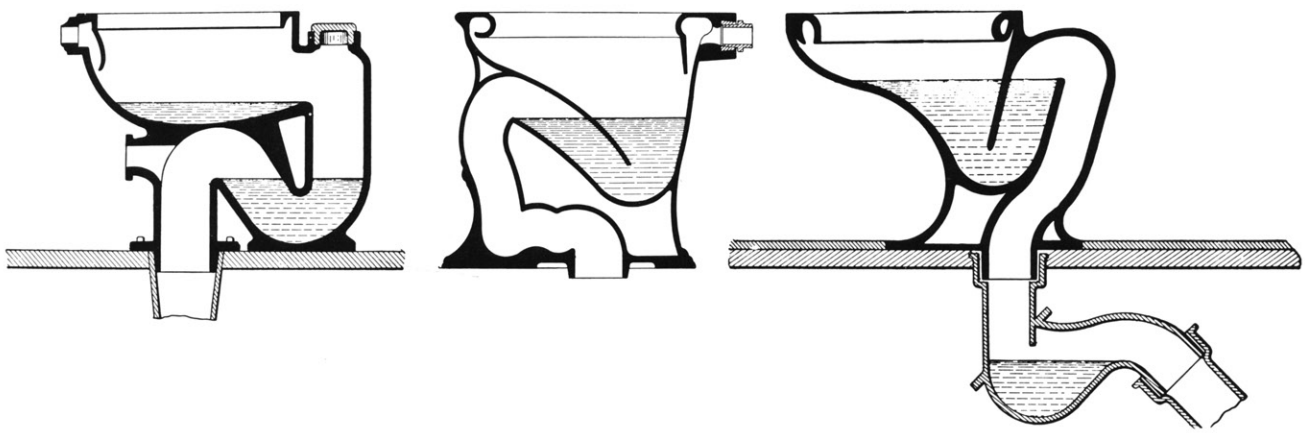


TYPES OF WATER-CLOSETS.

A Pan-closet.
B Valve-closet.
C Plunger-closet.
D Long-hopper closet.
E Short-hopper closet.
F Washout-out closet.

9.4 The basic types of water closets in the nineteenth century: *A*, pan closet; *B*, valve closet; *C*, plunger closet; *D*, long hopper closet; *E*, short hopper closet; and *F*, a washdown closet. (W. P. Gerhard, *House Drainage and Sanitary Plumbing*, 1882.)

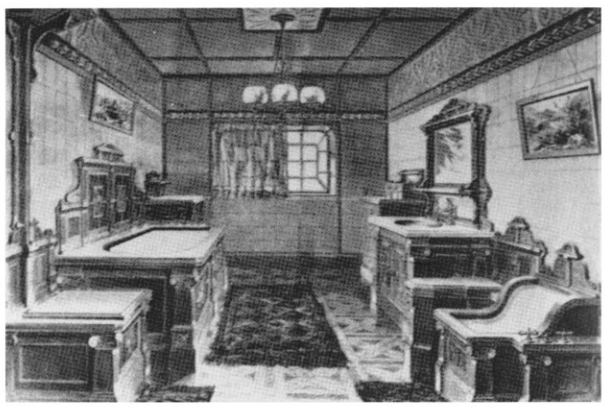
9.5 Later water closet designs: left, the washout closet; center, the washdown closet; and right, the siphon closet. (W. P. Gerhard, *Water Supply, Sewerage and Plumbing of Modern City Buildings*, 1910.)

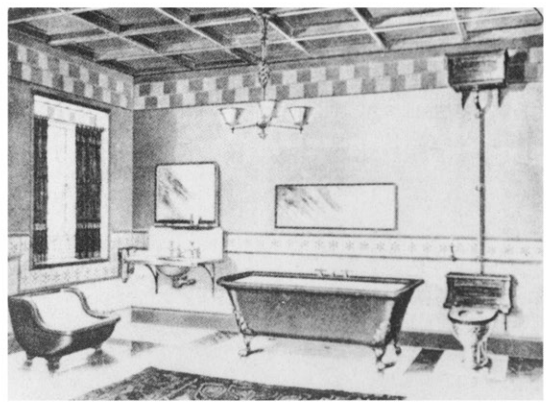


statistics available at the time. Over 10,000 copies of "Mr. Chadwick's Report" were sold, an extraordinary demand for anything published as a government document.[22] A series of boards and commissions contributed to the preponderant evidence that insanitary conditions were closely associated with the occurrence of disease and early death. Although not everyone was alarmed by the facts as they were reported, the righteous impulses of Victorian England were aroused. An exception was Thomas Carlyle, who declared that "if paupers are made miserable, paupers will needs decline in multitude."[23] Unfortunately Hamburg, Paris, and other cities were to make major improvements in their sanitary conditions before the political and business interests in London would permit such construction.

By the middle of the nineteenth century an increased portion of housing for English workmen was built with an alleyway behind, supplanting the back-to-back construction that had opened only at the front. Privies, often shared by several houses, were situated in rear yards, and the alleys permitted nocturnal removal of the privies' contents, which was sold to farmers as fertilizer. In some cases, instead of cesspits being emptied, other holes were dug and the previous pit merely covered, a practice that greatly increased the likelihood of polluting wells. Later the increased number of water closets installed resulted in larger amounts of fecal material entering streams, because it was no longer available for agricultural use.

Problems of building sanitation, while more prevalent in slums, were forthrightly disrespectful of rank. In 1844, 53 overflowing cesspits were found beneath Windsor Castle, providing an explanation of the frequent ailments suffered by the royal family's servants at the castle. The Prince Consort ordered the installation of water closets and a sewage system. Seventeen years later Prince Albert died of typhoid fever, and a decade afterward the Prince of Wales fell ill of the same disease. Such events brought the attention of the English public to bear upon the need for improved household sanitation. The





Prince of Wales, after recovering from his nearly fatal fever, was said to have declared, "If I were not a prince, I would be a plumber."[24] But progress was slow. In 1882 the Duchess of Connaught, wife of Victoria's third son, was dangerously ill, and the ailment was attributed to her newly built residence, Bagshot Park. The duchess's doctor and a civil engineer inspected the building and reported: "Offensive smells had long been perceived about the house, and had been a common topic of conversation; but no one had suspected their origin or had realized the dangers they were likely to cause. Many of the inmates, however, had suffered from various forms of indisposition, such as sore throats, diarrhea, and a general sense of heaviness and malaise, and these generally affect new comers."[25] *Lancet*, a medical journal, commented that the plumbing system of the building appeared to have been designed "by a Machiavellian policy which would seem to be the pastime of modern builders."[26]

In Great Britain the first legislation on sanitation, enacted in 1848, had little effect because it gave permission for improvements without requiring that any action be taken. A succession of later acts established standards and required compliance with them. As legislation advanced, the training of inspectors improved and their numbers increased. In 1864 Dublin had only one sanitary officer, but about 30 years later the city employed a corps of 50.[27]

A reform movement in New York, led by concerned businessmen, in 1864 conducted a survey of sanitary conditions within the city, using procedures that had been developed in England. Their report of shocking conditions and the threat of cholera led to passage of the Metropolitan Health Law two years later. Used as a precedent for many sanitation laws of other cities in the United States, the Metropolitan Health Law and subsequent stricter legislation were particularly directed toward the control of tenement construction.

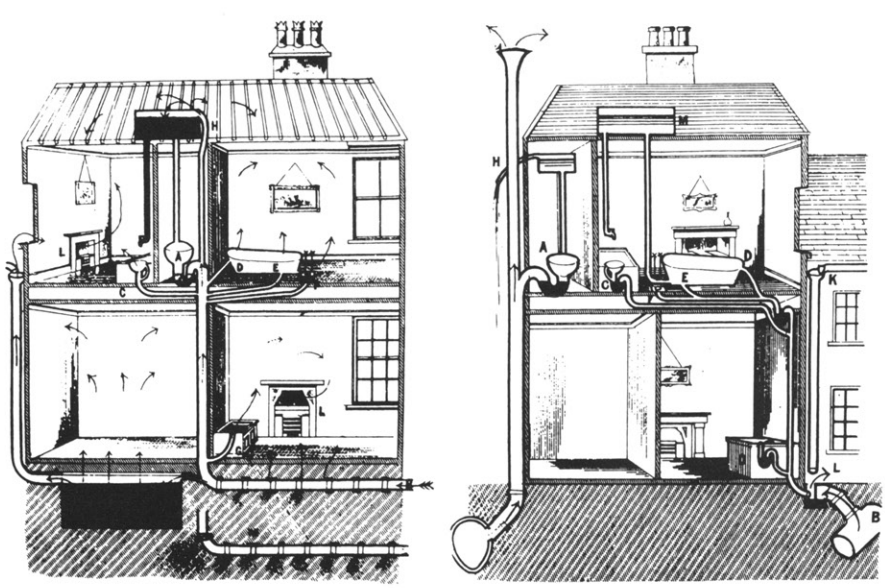
9.6 Bathrooms of the well-to-do in the United States: During the 1880s (left) it was deemed necessary to encase all fixtures in wooden paneling, a requirement no longer present in the 1890s (center) when open fixtures were given decorative treatments. By the start of the twentieth century (right) a shower over the bathtub was standard. The presence of sitz baths and bidets in these catalog illustrations indicates the enthusiasm of the manufacturers of plumbing fixtures more than the common practice of the times. (A. M. Maddock, *The Polished Earth*, 1962.)

One of the most important factors in protecting the public health was the provision of a safe water supply. In 1829 sand filter beds were installed by the Chelsea Waterworks in London, and about 20 years later all water companies in the city were required to do the same. At the end of the century there were in all almost 15 acres of sand filter beds in London. At the same time techniques of filtering water in the United States proved so effective that sanitary engineers recommended that municipal authorities invest only in water treatment, because, as one engineer put it, a dollar spent on water treatment "would do as much as ten dollars spent in sewage purification."[28] There was, of course, a sharp difference of opinion between the citizens of a small downstream town and those of the upstream metropolis. However, it was discovered in Lawrence, Massachusetts, that sand filtration reduced the incidence of typhoid fever by 79 percent.

Early pipes, those of the ancient and medieval periods, were made of earthenware, lead, or wood. For drains made of fired clay it was simple to taper or enlarge tubular shapes in order to provide a firm joint between lengths of pipe. Sheet lead was obtained by spreading the molten metal on a sand-covered surface and beating the sheet until the desired thickness was attained. An oval cross section resulted from bending the sheet lead and making a soldered joint; a teardrop cross section resulted when the metal was folded and crimped for a joint. Wooden pipes have been found in several early medieval English installations, notably monastic complexes. Early in the seventeenth century, when the first large-scale water supply system was available in London, water was brought from the north into the city by an open stream 38 miles long, and from a reservoir it was distributed to users through mains made of elm trunks and fastened together with iron bands. Branches of the trees were often used to form Y's and T's needed for water mains. In spite of the development of metal pipe, the use of wooden mains for the supply of water and gas persisted into the last decades of the nineteenth century. The American Pipe Company of San Francisco in 1878 advertised sections of fir and pine 8 feet long, which were bored, steam-treated, wrapped with iron bands, and coated with asphalt.[29] Wooden pipes must have done their work well. In one of the company's advertising brochures a testimonial letter reported the excellent condition of wooden water mains in Manhattan that had survived more than 75 years of use.

Metal pipes for water supply were later made by the same methods employed in manufacturing gun barrels. In fact, many early installations for water supply, gas lighting, and steam heating utilized inexpensive gun barrels, those that were a manufacturer's surplus or were judged unsatisfactory for the sudden pressure of firing a rifle.

The principal concern in plumbing systems was the piping of drainage systems that carried away the waste, and tell-tale odors were ample indication that the drains were not satisfactory. A major factor in the public's anxiety about drains was the fact that the "miasma theory" of disease's ori-



9.7 A publication of 1879 shows "a house with every sanitary arrangement faulty" (left) and "a house with faulty arrangements avoided" (right). Arrows within the dwelling at left show the possible circulation of sewer gas leaking from fixtures and seeping from beneath the floors. (T. P. Teale, *Dangers to Health*, 1879.)

gins and transmission persisted in the minds of the public and many physicians long after the conclusive experimental determination of the "germ theory." Unseen microorganisms were recognized as the source of disease by the 1880s, but only among those of advanced scientific background. Most of the population continued to associate the spread of sickness with the presence of identifiable foul odors.

Sewer gas leaked into toilet rooms primarily through early water closet installations (fig. 9.7). "The odor of their memory, or the memory of their odor, still lingers with us."[30] An almost endless number of ailments were attributed to the presence of sewer gas. In addition to its supposedly causing specific sicknesses, there was a more general claim that sewer gas deprived "men of ambition and women of beauty." As late as 1901 William Paul Gerhard, a leading sanitarian in the United States, told a gathering of knowledgeable health officers: "Modern German sanitarians are nearly united in being opposed to the so-called 'sewer-gas theory;' they claim that the researches of Von Pettenkofer, of Pasteur, of Dr. Koch and others have established, almost beyond a doubt, the fact that every infectious or zymotic disease requires the presence of a specific microörganism or pathogenic bacterium to cause it, and that the gases of putrefaction *per se* cannot cause the disease."[31] Another authority considered that sewer gas, while not a cause of specific disease, made one susceptible because it produced a condition of general ill health.

The primary defense against sewer gas entering a building was the trap, which was intended to seal drains by means of the water retained in a downward bend of the pipe. There was a danger, however, of water in a trap evaporating when buildings were closed for a long period, but hardly so great a danger as imagined by Chicago plumbers who in an 1888 issue of the *Sanitary News* recommended filling such traps in vacant buildings with glycerine or oil, or even draining out the water and packing the trap with salt.[32] A more realistic danger was that downrushing quantities of water in the main drains might create a vacuum and draw water out of a trap. The solution proposed was venting each trap by extending a pipe from the down side of the trap through the roof, and so providing air to relieve any vacuum (fig. 9.9). A Chicago plumber remembered that he first saw a major vertical drain extended through the roof in structures after the fire of 1871.[33] In the previous decade he had seen vents installed in connection with water closet traps, but they had been meant to avoid pressure developing within the major drains rather than to protect the seal of traps. By the end of the century regulations often called for back-venting traps. This requirement, still in force, was debated with great fervor. The opposition was formidable and outspoken.

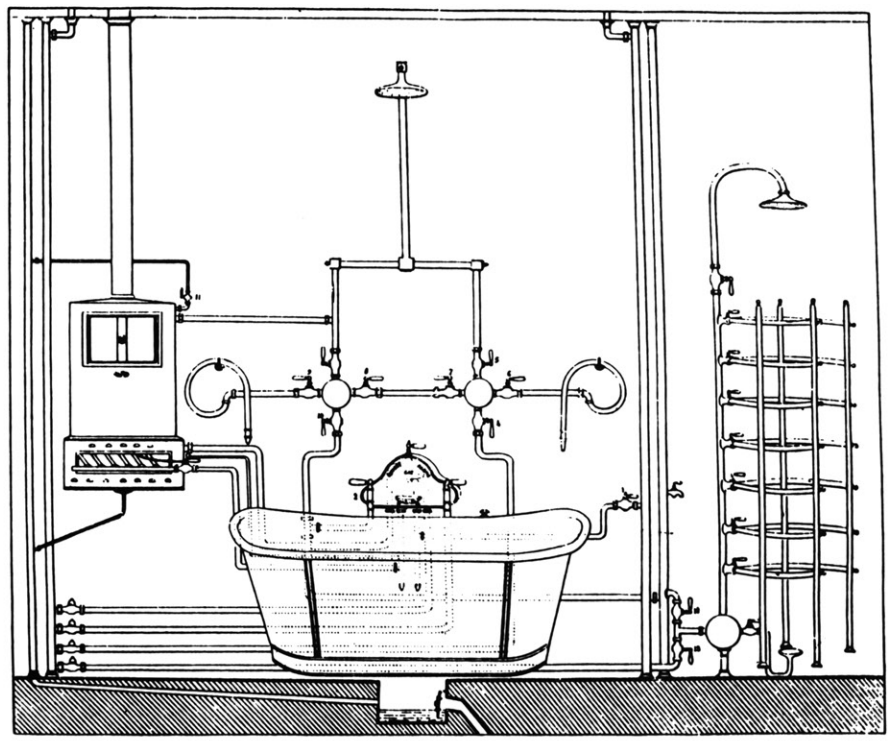
J. Pickering Putnam, a Boston architect: "One of the most unfortunate and burdensome building-laws ever inflicted upon the people, and an imposition upon the public."

George E. Waring, the famous New York City sanitarian: "Does more harm than good, that is to say, that a trap is more likely to lose its seal if it is back-vented than if it is not."

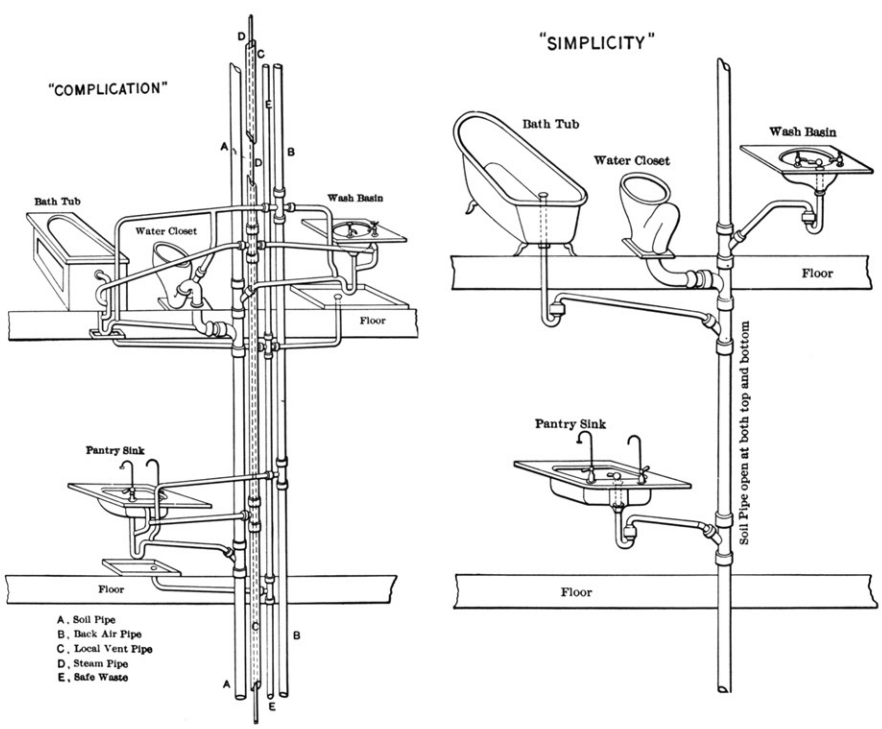
An "English expert on drainage:" "A diagram of house-plumbing, protected by ventilation-pipes as prescribed by most American authorities, a bewildering nightmare of complicated ingenuity."[34]

In 1892 the *Northwestern Architect*, a Minneapolis publication, queried

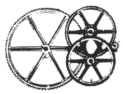
9.8 In commenting on this 1890 bath arrangement displayed at the Palais de l'Industrie, *La Construction Moderne* said, "This system is perhaps extremely ingenious but less than practical." The journal's illustration bore 21 lines of caption explaining the ways of achieving different bathing effects. (*Construction Moderne*, 20 December 1890.)



9.9 Diagrams at the turn of the century suggested eliminating "back air pipes" by care in the provision of special traps. Such precautions permitted simplification of the piping required. (R. Sturgis, *Dictionary of Architecture and Building*, 1901–1902, vol. 2.)



architects and plumbing contractors on the matter. Plumbers were about evenly divided on the subject of back-venting. The architects gave varying replies, but all were convinced that traps of greater depth than customary would provide as much protection as back-venting. This point of view was echoed by Dankmar Adler, the respected Chicago architect, who added, "I am glad to see that you are moving in the cause of reform in a matter which is of vital interest to the entire community."[35]



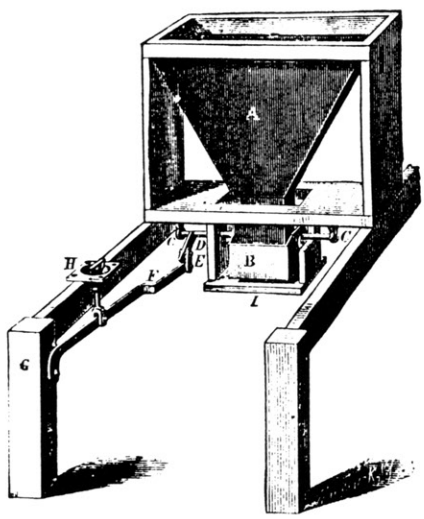
Since ancient times the disposal of wastes has been accomplished with the use of water. Water closets, by definition, consumed large amounts of water, and even the filth thrown into streets was washed into rivers and lakes. There were few exceptions. The "night-men" who gathered the contents of cesspools, privy pits, barrels, and buckets sold them to farmers when cities were so small that a short trip outside the city would be profitable. When the distance was too great, the excrement was usually deposited in a single large pit or, more likely, taken to the river. The construction of metropolitan sewage systems and the increased number of water closets unfortunately meant only that an even greater portion of the waste went into the river.

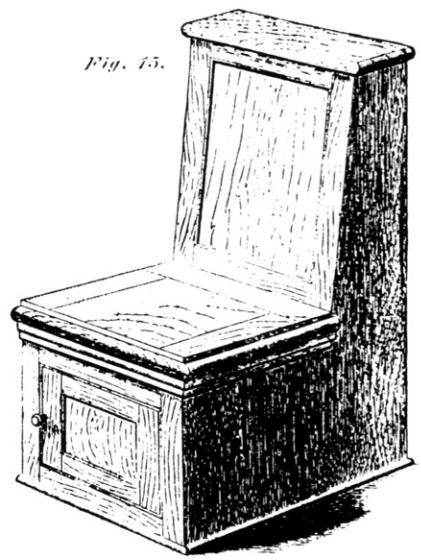
"No more pipes, no more cesspits, no more unhealthy odors, absolute cleanliness." When a writer for *La Construction Moderne* read those claims for the earth closet invented in 1860 by the Rev. Henry Moule, he accepted the first and second claims, questioned the third, and rejected the last.[36] Lime, ashes, and sand had long been periodically dusted over the contents of privies (fig. 9.10). In the Moule earth closet, fine, dry earth or sand was kept in a hopper above and behind the seat. After each use a lever released a layer of earth from the hopper and, if ashes were used, gratings retained the cinders. One version of the earth closet automatically activated the hopper whenever a user rose from the seat, but the contraption appears to be have been noisy. "In sick rooms, this method of distribution of earth may be found objectionable, as more or less vibration follows the rising and this is apt to disturb the nerves of a patient."[37] The earth closet enjoyed a limited popularity, and there were nine designs patented in the United States between 1872 and 1882. Much of this interest in what now seems an improbable solution to the problem came from cold regions in which water pipes were liable to freeze. In addition, it should be recalled that the earth closet may have offered a relatively inexpensive alternative at a time when about 95 percent of New York City's population still depended on privies or chamber pots.[38]

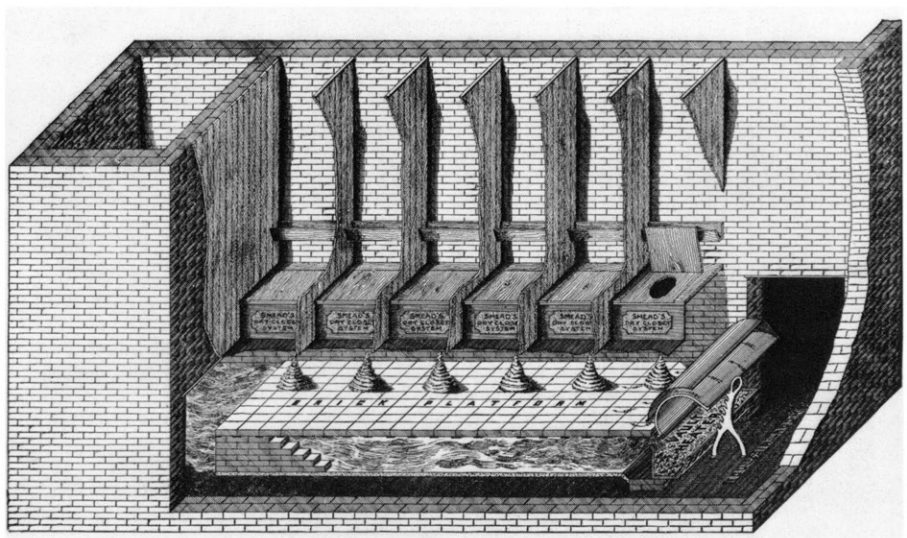
The earth closet was a short-lived invention. Chemical toilets containing liquids of high alkalinity have become the most common solution for toilets in temporary locations, and pit privies remain a characteristic of isolated and primitive locations. The discussion of methods for disposing of human wastes has in recent years been related to discouraging forecasts of the future water supply. Toilets employing bacterial decomposition, incineration, and oil as a flushing agent have received attention, but almost all modern systems are fundamentally based on Harington's design made at the end of the sixteenth century. The water closet of that time has been improved in operation and appearance, but little has been done to confront the fact that water-flush systems are manifestly inappropriate in our time.

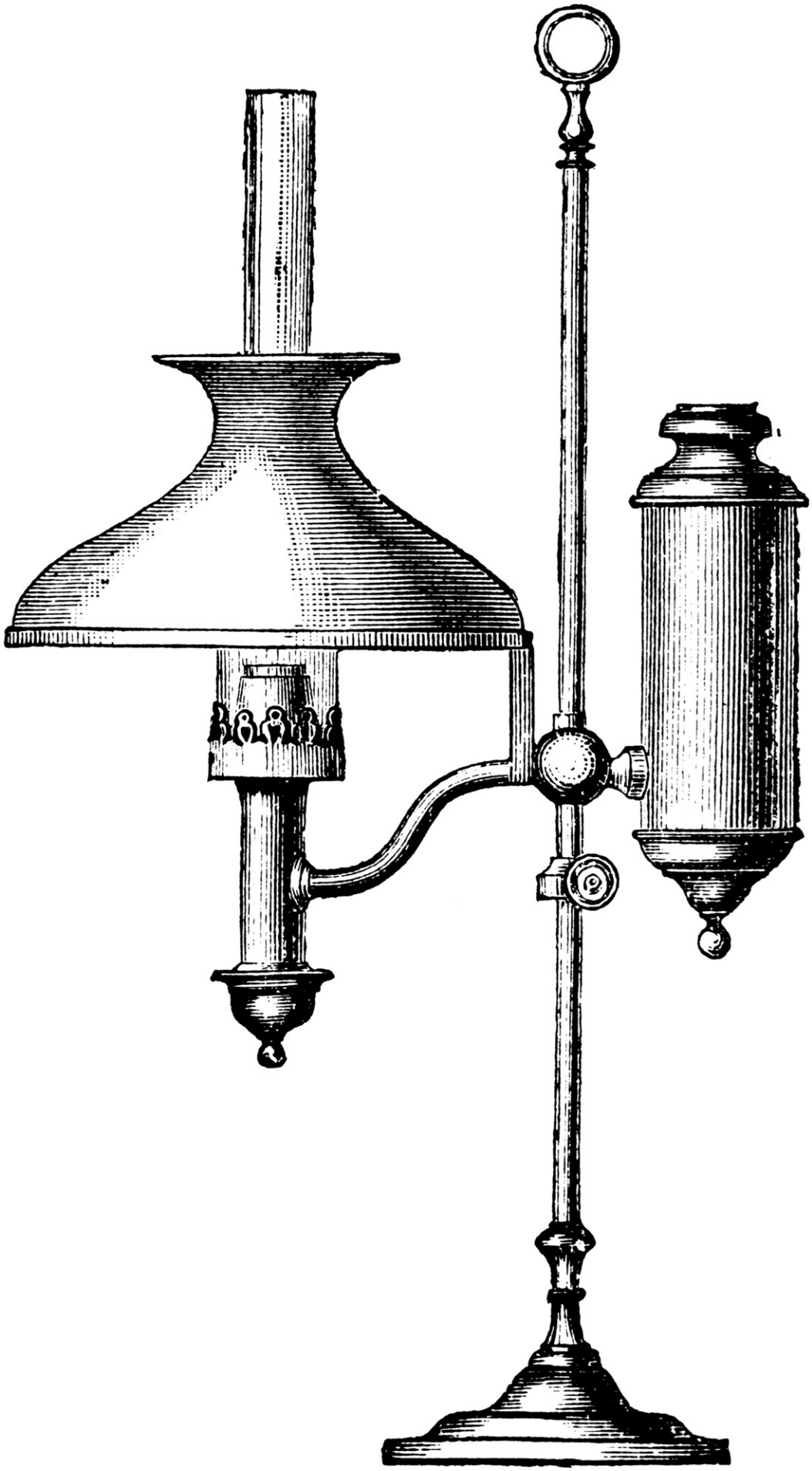
9.10 Earth closets scattered soil, sand, or ashes over the wastes deposited in a box beneath the seat. (G. E. Waring, *Earth Closets and Earth Sewage*, 1870.)

9.11 Systems of sanitation that avoided the use of water were particularly fitting for northern areas, where frozen pipes were a constant problem. For the Smead Dry Closet and Cremation System, a chamber was constructed beneath the floor of a school toilet with air going over a heater at one side (right) and up a flue on the other side (left). According to an 1889 catalog, over a hundred of these systems at that time had been installed in schools in Minnesota and Wisconsin. (Catalog of Ruttan Warming and Ventilating Co., 1889.)









Technics and Architecture

The Development of Materials and Systems for Building

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1660s Experiments conducted with gas gathered from springs

1783 A circular burner for oil lamps invented by Genevois Aimé Argand

1798 Philippe Lebon moves to Paris to develop his "Thermolampe"

1802 Peace of Amiens celebrated by William Murdock's gaslight display at the Boulton and Watt factory, Birmingham

1829 Limelight perfected by Thomas Drummond (Britain)

1845 Patent (Britain) awarded for incandescent lamp of J. W. Starr

1859 Moses G. Farmer lights his home in Salem, Massachusetts, with an incandescent lamp

1870s Continuous electrical current provided by the Gramme dynamo

1876 The Jablochkoff arc lamp introduced in Paris

First demonstration of Charles Francis Brush's arc lamp in Cleveland, Ohio

1879 Thomas A. Edison obtains his principal U.S. patent for the incandescent lamp

Joseph Swan exhibits his incandescent lamp before the Newcastle-upon-Tyne Chemical Society

1893 Commercially practical incandescent mantles for gas burners developed by Carl Auer von Welsbach

1895 D. McFarlan Moore displays his first vapor lamp

1907 Tungsten filament incandescent lamps introduced

1939 Planners of the New York World's Fair obtain fluorescent lamps for use in fair buildings

The primitive firebrand taken from a campfire appears to have been the root from which a minor industry had grown by the seventeenth century. Sticks of pine and other resinous woods were shaped for lighting, and stands, brackets, and ash pans in considerable variety were manufactured to hold such torches. Other vegetable matter was burned for light, such as the oily nuts of the candleberry tree in Southeast Asia, and in some areas that had little plant life the oily carcasses of certain fishes and birds were burned. Through time each of these alternatives acquired its own fixtures and accessories.

From Roman times candles were often made of beeswax (plentiful at a time when honey was the usual sweetener), and tallow candles were made by rendering animal fats. There was also the relatively inexpensive light available from the rushlight, which was made by dipping the pith of rush stalks in tallow. The outside material of the stalk was left on one side of the pith as a stiffener.

Tallow candles flickered and smoked, but wax candles were many times more expensive. A "composite" candle, made by mixing tallow and wax, was more reasonable in price and long served as a popular compromise. In the early years of the eighteenth century, whalers turned their attention to the sperm whale, which had body tissue rich in oil and in the front of its brain had a cavity that contained oil and spermaceti. The oil and spermaceti mixed together at the body temperature of the whale, but when cooled the spermaceti separated and set as a white wax. Of this were made the finest candles, the standard against which later lighting systems were compared.

As candlewicks charred, the amount of light delivered by the flame was reduced. This problem was so great that in seventeenth-century theaters the chandeliers were lowered between acts, and the actors—still costumed as heroes or buffoons—came forth to crop "snuffs," the charred ends of wicks, so that there might be brighter light for the act that was to follow. Starting around 1810 braided wicks were soaked in boracic acid, and after this treatment the wicks would burn away more completely, improving the candle's light.[1] It was estimated that a typical Philadelphia family of five members at the first of the eighteenth century would have had two oil lamps for those rooms most used, perhaps the parlor and the kitchen, and five candlesticks for errands into other rooms or going off to bed.[2] As faint as its light might be, a candle was safer than a lamp, for lamps could spill their fuel when overturned.

The earliest lamps were little more than shallow dishes with tubular spouts in which lay a wick. With a thick wick and limited air supplied to the flame, such oil lamps could provide little light. The first fuels used were olive oil in the south of Europe and animal oils, including that of whales, in the north. In the middle of the seventeenth century the introduction of colza oil, made from rape seed, reduced lighting costs to such an extent that many poor families could afford light better than had been provided by their lamps filled with the animal grease they saved.[3]

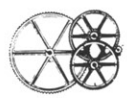
In spite of changes in the form of wicks and the lamp itself, the oil lamp gave off a weak and wavering light. A major improvement was made in 1783 by a young Swiss scientist, Genevois Aimé Argand. Argand demonstrated his lamp to the police administrator responsible for lighting Paris streets; meeting a cool response, he traveled on to England, where he found an opportunity to present George III

10.1 This popular kerosene-burning student's lamp had a reservoir (at the right) that released fuel to the base of a cylindrical Argand wick. An ingenious valve controlled the kerosene's flow and made it possible to place the tank of fuel at the side, so that it did not prevent ample light falling downward, where it would be needed on a student's reading table. (*Appleton's Cyclopedia*, 1880, 2:225.)

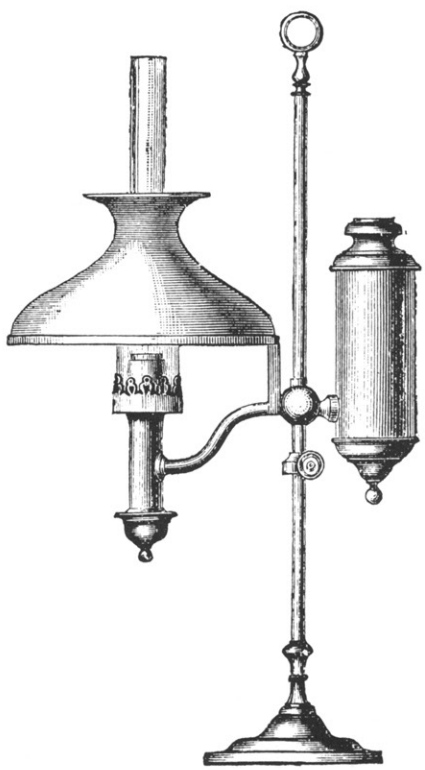
with a model of his lamp. With the king's encouragement, Argand soon was introduced to Matthew Boulton, James Watt's partner, and they patented the lamp and set up a factory to manufacture it.

The Argand lamp recognized the need to provide ample air to a flame. The reservoir of oil was shaped in a ring with an opening through its center. Around this opening a hollow tubular wick stood in the circle of fuel. Argand's design permitted air to rise around and in the center of the flames, establishing a draft like that of a chimney. (The same form was later used in Argand burners for gas lighting.)

In 1785, feeling assured of his invention's success in England, Argand returned to France to try once more for official recognition of his lamp. To Argand's amazement, both the court and Paris were filled with talk about the marvelously brilliant lamps that had lighted a performance of the *Marriage of Figaro* at the Comédie-Française. Although he had not known that they were to be used, newspaper accounts awarded Argand credit for inventing the lamps. At the same time credit for the use of glass cylinders around the flames was given to Quinquet and Lange, a pharmacist and a grocer who had been part of Argand's circle of scientific enthusiasts when he lived in Lyons. Argand protested loudly, and when he applied for a French patent he met with resistance from his former friends. Waged in newspapers, at scientific conferences, and even before the Parlement, the debate boiled down to this: Lange had displayed a lamp with a glass chimney to the Académie des Sciences more than four months before Argand's application for an English patent was filed, and while Argand's English patent included a chimney, there was no stipulation that it be of a transparent material. In the end the French authorities granted Argand exclusive rights to manufacture the lamps, and Lange was given exclusive rights to market them. Quinquet, on the other hand, through some private arrangements with the other two, displayed and sold a small number of the lamps in his apothecary shop.[4]



Near Wigan, a Lancashire town just west of Manchester, the pools of a small spring bubbled with strong-smelling vapors. Natives believed that the water was flammable, but Thomas Shirley tested it and found that the water was merely water. It was the foul air that floated on the surface of the water and the rising bubbles that caught fire from a torch. This he reported to the Royal Society in 1667. At about the same time Rev. John Clayton wrote the prominent scientist Robert Boyle describing similar stud-

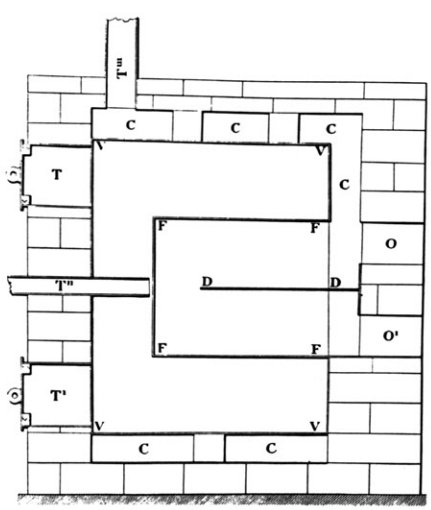


ies he had made. Conjecturing that the vapor in such streams must seep up from the strata of coal that underlay much of the region, Clayton had heated coal in a closed vessel.

> At first there came over only Phlegm [water], afterwards a black Oil [coal tar], and then likewise a Spirit arose, which I could in no ways condense, . . . I observed that the Spirit which issued out caught fire at the Flame of the Candle, and continued burning with Violence as it issued out in a stream, which I blew out, and lighted again, alternately, for several times.[5]

To entertain friends Clayton inflated bladders with the gas, then pricked the bladder with a pin and lit the thin stream of gas that spurted out as he squeezed the bladder.

In all such early experiments no proposal seems to have been made for the use of gas for lighting or heating. It seems to have been viewed as a curious phenomenon without particular utility, until 1765 when the English town of Whitehaven briefly considered the possibility of piping gas from a nearby coal mine to light the town.[6]



10.2 The gas-producing system patented by Philippe Lebon is shown in cross section. The material from which gas is to be extracted is inserted through one door (*T*) and removed through another (*T'*). Within the retort (*V*) is a firebox (*F*) inside which the fuel rests on an iron plate (*D*), its heat reaching the flue (*T'''*) through channels (*C*) around the retort. The "Thermolampe" was a refinement of this scheme with gas-burning lamps attached to it. (C. Hunt, *History of the Introduction of Gas Lighting*, 1907.)

Experiments in the middle of the seventeenth century initiated more than a century of further study without appreciable consideration of gas's large-scale practical application. One investigator discovered that when coal gas was passed through tubes immersed in water some matter would condense, while the gas retained its flammability. A bishop in Wales investigated the gases coming from different kinds of coal and wood when they were heated in a closed retort. Jean Pierre Minkelers, a Belgian professor of science, was paid in 1784 to explore ways of producing light gases for use in balloons, only a year after Montgolfier's first hot-air balloon ascension. One of the first of the substances considered in his investigation was coal gas and, while this proved not to be suited for use in balloon ascensions, it was used to light Minkelers's laboratory.

At the end of the eighteenth century two men, a Frenchman and a Scot, took steps toward commercialization of gas lighting. The Frenchman, Philippe Lebon, was an engineer and chemist who experimented with the distillation of wood in an iron retort and realized that the gas could be useful for heating and lighting (fig. 10.2). In 1798 he moved to Paris and continued his experimentation. After obtaining a patent, Lebon sought to interest the French government in using gas to light the public buildings of Paris, but in the rising flood of Napoleonic ambitions the proposal was passed over. Lebon's "Thermolampe" was a self-contained unit that both produced and burned the gas. A few gardens and a few houses in Paris were lighted by this system, but after Lebon's early death the system failed to become popular, in spite of his widow's vigorous efforts to market it.

The Scot was William Murdock,

son of a millwright who taught him that craft. In 1777 he was hired to work in the Boulton and Watt factory where steam engines were built, and two years later he was sent to the county of Cornwall to assume responsibility for installing and maintaining the pumping engines used in mines there.

> It is now [1806] nearly sixteen years since, in a course of experiments I was making at Redruth, in Cornwall, upon the quantities and qualities of the gases produced by distillation from different mineral and vegetable substances, I was induced . . . to try the combustible properties of the gases produced from it [coal], as well as from peat, wood, and other inflammable substances. And being struck with great quantities of gas which they afforded, and as well with the brilliancy of the light and the facility of its production, I instituted several experiments with a view of ascertaining the cost at which it might be obtained, compared with that of equal quantities of light yielded by oils and tallows. My apparatus consisted of an iron retort with tinned copper and iron tubes, through which the gas was conducted. . . . The gas was also washed with water, and other means were employed to purify it. In the year 1798 I removed from Cornwall to Messrs. Boulton, Watt and Co.'s works for the manufactory of steam engines at the Soho Foundry [Birmingham], and there I constructed an apparatus upon a larger scale, which during many successive nights was applied to the lighting of their principal buildings. . . . These experiments were continued with some interruptions until the peace of 1802, when a public display of this light was made by me in the illumination of Mr. Boulton's manufactory at Soho. . . . Since that period I have, under the sanction of Messrs. Boulton, Watt, and Co., extended the apparatus at Soho Foundry so as to give light to all the principal shops.[7]

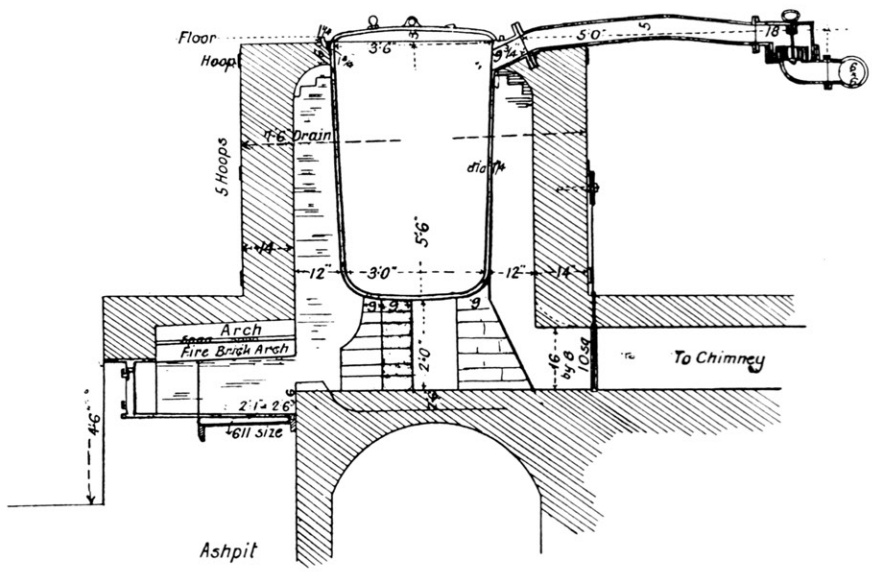
Many years later the Scottish engineer William Fairbairn recalled a walk through an unlighted part of Manchester as Murdock pressed on a gas-filled bladder, as if it were a bagpipe. Their way through the night was lighted by a flame at the end of a clay pipestem that Murdock had attached to the bladder.

When Murdock returned to the Soho factory, a brief period of experimentation with gas was followed by a hiatus of about two years, during which the system appeared to be unpatentable because of litigation. Efforts resumed in late 1801 when one of Watt's sons wrote giving news of Lebon's activities in Paris. A few months later the Peace of Amiens provided the opportunity Murdock described for introducing gaslight to the public. A retort was set in a fireplace of the major factory building and tubes led gas from there to copper vases that served as lanterns at the ends of the building.

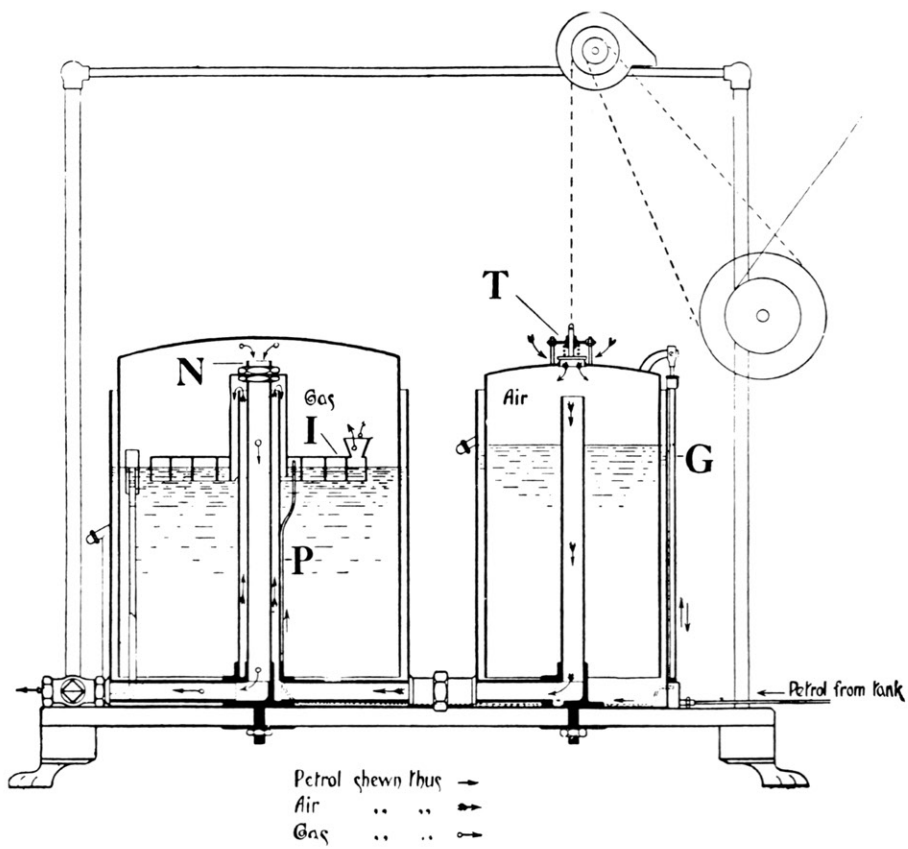
George Augustus Lee, a partner in Phillips and Lee, a leading cotton-spinning concern, arranged in 1804 for a gas system to be installed in his house, and the project expanded to include two rooms of the mill and the company's accounting offices (fig. 10.3). When the gas system later grew to encompass all the mill building, there were a total of 271 Argand burners and 633 cockspur burners which, according to Murdock's calculations, cost only a fraction of what would have been spent for tallow candles. In addition, there were some savings in insurance rates, for underwriters viewed the highly combustible, lint-filled mill buildings as very high risks.[8]

Although Murdock stated in 1808 that he was "unacquainted with the circumstances of the gas from coal having been observed by others to be

10.3 William Murdock provided lighting for England's largest textile mill by installing six iron retorts of this type, each 5½ feet high. Coal was lowered into the retorts in metal baskets. The gas was piped to an air-cooled condenser from which tar was drained. (C. Hunt, *History of the Introduction of Gas Lighting*, 1907.)

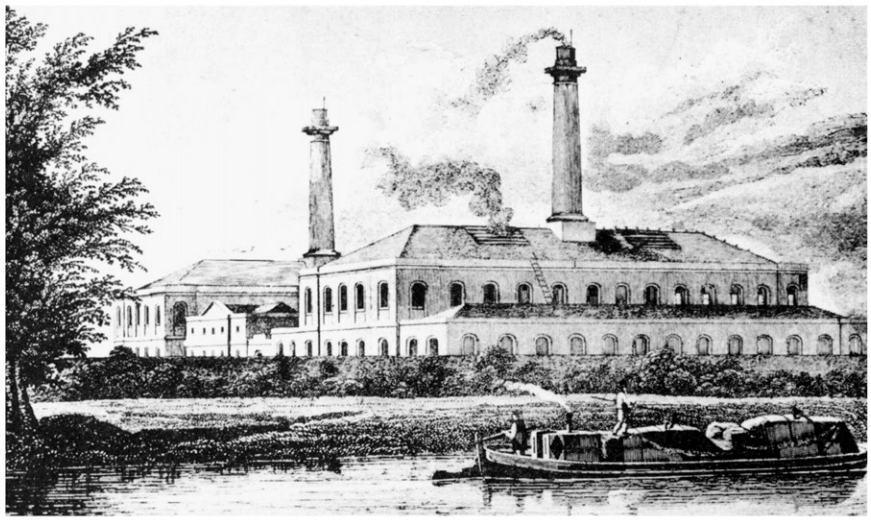


10.4 Early in the twentieth century, English country houses could escape from the use of candles and lamps by installing their own gas systems, such as the "Country Petrol-Air Gas Plant." The air-pumping bell (right) was suspended with counterbalancing weights and provided pressure. The movement of this bell operated a pump (*G*) that supplied small amounts of gasoline to the upper part of the large tank (*I*) from which a gasoline-air mixture of between 2 and 6 percent went to the lighting system. It was said that 100 to 120 gas burners could be operated with one gallon of gasoline per hour. (*Nature*, 6 January 1916.)



capable of combustion," when the Gas Light and Coke Company applied to Parliament for incorporation, Murdock's enterprise with Boulton and Watt was not judged to be singular, in spite of the firm's vigorous battle in the hearings. James Watt the younger led the fight, with George Augustus Lee giving testimony and the case being presented by Henry Brougham, later to become a political reformer of governmental practices. After competition had been widened in the field of gas lighting, Murdock lost interest in the subject, and in 1830 he retired from Boulton and Watt to his house nearby, which was lighted with gas from the Soho plant.

When Murdock completed his installation at the Phillips and Lee mills, he reported that there was "no Soho stink," which makes it clear that at Soho any purification had been primitive and inadequate. The early displays of gas lighting were most often outdoors and a majority of early installations were in large spaces such as theaters and mills, because the fumes from gas lamps were found to soil furniture, to damage goods in shops, to cause a room's occupants to have headaches, and to have an extremely foul smell. One of the early schemes for lighting residences with gas proposed placing lamps outside windows with reflectors to direct light into the house. Thus light would enter while odor was kept out, and gaslights would not add to the monumental task of spring housecleaning, a tradition required by lamps and open fires.

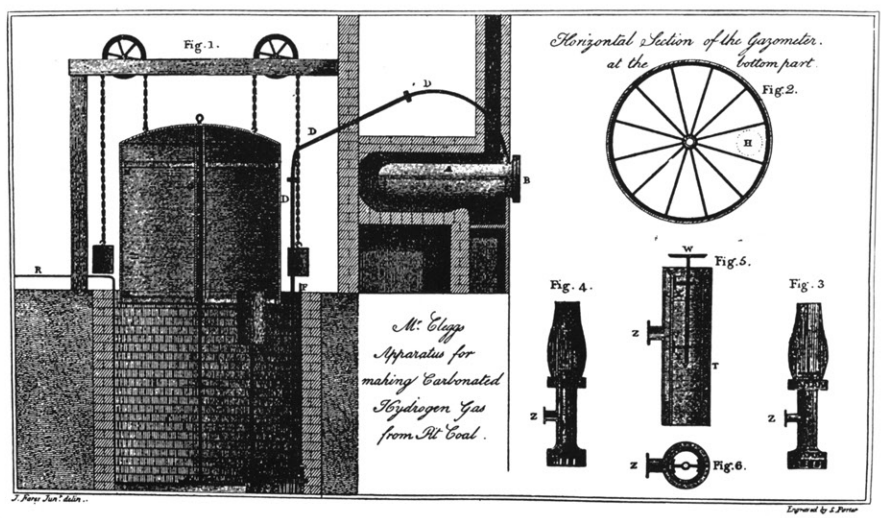


10.5 In 1815 the first gas supply in London started with 15 miles of mains. Thirteen years later the area to which gas was supplied was much larger, and this gasworks with two halls containing retorts loomed near the Regent's Canal. (Nineteenth-century engraving. Reprinted from D. Chandler, *Outline of History of Lighting by Gas*, 1936.)

Once gas lighting began to spread in popularity, methods of purification demanded and received attention, perhaps more than was given the basic procedures of gas production. Removal of impurities was first accomplished by passing the gas through masses of moistened coke, through tanks of water, or through fine sprays of water. These practices drew off some by-products but did little to improve the gas. Samuel Clegg, who had been Murdock's assistant at Soho, added caustic lime to water and forced the gas to bubble through this mixture. However, the pressure resulting from this treatment caused problems in the early stages of production. A later method of purification, long used, was accomplished by placing two or three inches of moist lime on trays and forcing the gas through several of them. After it had been used, the lime was extraordinar-

10.6 Although overturned oil lamps had always presented a danger, the explosion of gas was more feared. There were many tales of asphyxiation, and some experts recommended that gas not be piped to bedrooms. In residences, one was constantly reminded of these risks by the loud pop when a burner was lit and by the faint pervasive odor of illuminating gas that leaked from pipes and burners. (F. L. Collins, *Consolidated Gas Company of New York: A History*, 1934.)

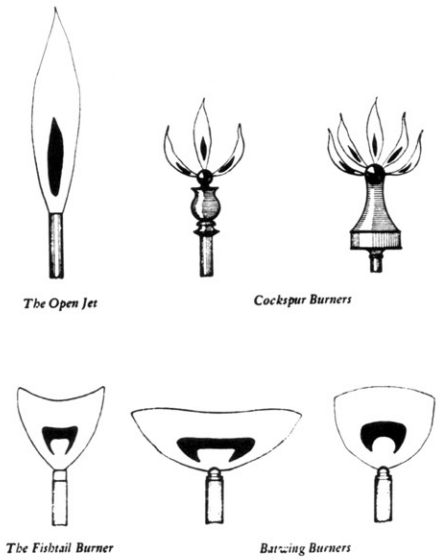
10.7 In Samuel Clegg's systems for factory gas lighting, coal was put in an iron retort (*A*) beneath which the fire was built. A pipe (*D*) led the gas to a tank of water in which a gas holder was suspended by counterbalances. (C. Hunt, *History of the Introduction of Gas Lighting*, 1907.)



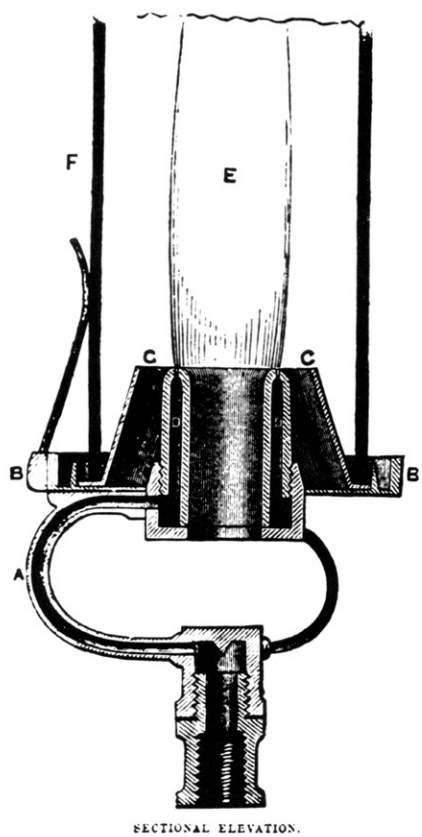
ily odoriferous, but it could be sold to farmers as fertilizer. London's Gas Light and Coke Company evaporated the stinking liquid that came from the lime process and carted it away at night, during the hours when the cleaners of cesspools also scheduled their work.[9]

As gas became tolerable, attention focused on the efficiency with which it might be burned, particularly on devices that could increase the amount of light gained from a jet of gas. The first form of gas burner, a single small hole in a tip applied to the end of a gas pipe, soon came to be used only in places that required little light or merited only the cheapest burner (fig. 10.8). The cockspur burner, in Murdock's words, consisted of "a conical end, having three circular apertures . . . one at the top of the cone, and two lateral ones." He described the shape of the flame as resembling the fleur-de-lis, but the flames' similarity to a fowl's footprint caused cockspur to be the common name for the burner. The cockscomb burner was an extension of the same design, with the tip a flattened fan-shaped piece on which the outside edge had as many as ten holes. The batwing burner had a hemispherical tip with a narrow slit from which the gas issued. Its flame spread to such an extent that glass chimneys, which increased the draft and protected the flame from wind, were seldom used because the width of the flame could cause the glass to break.[10]

All of those were elementary variations on simple openings. The union-jet or fishtail burner used a different course. The tip was flat or slightly concave and two holes were drilled at about 45-degree angles so that the jets of gas would strike against each other. This spread the gas and produced a flat flame like that of the batwing burner, but longer and narrower.



10.8 These standard types of gas burners were developed between 1808 and 1820. The corrosion that troubled burners made of iron and steel was eliminated by using enamel, soapstone, porcelain, and other materials. This change provided a slightly brighter light, for such burners did not draw heat away from the flame so rapidly. (F. L. Collins, *Consolidated Gas Company of New York: A History*, 1934.)



SECTIONAL ELEVATION.

A—Supply-tube to chamber of combustion
B—Support for chimney.
C—Cone, outer air supply.
D—Steatite chamber of combustion.
E—Flame.
F—Chimney.

10.9 Argand gas burners derived their name and design from the cylindrical-wick oil lamp invented late in the eighteenth century. Air moved within and around the ring of many gas jets. It was found that a small number of holes increased velocity of the gas and reduced the amount of light given off. The height of the glass chimney could be varied to compensate for gas of low quality. This is the 1869 Government Standard Burner, serving in England as a means by which the quality of gas could be determined. (D. Chandler, *Outline of History of Lighting by Gas*, 1936.)

10.10 Almost to the end of the nineteenth century, limelights persisted as theatrical spotlights and for magic lantern projectors. In this piece of theater equipment, a cylinder of lime was set on the spindle beside the gas jet at the right. As the lime burned away, intensity of the light could be sustained by rotating it with the knob at left. (*The Magic Lantern*, 1890.)

10.11 Lamp governors contained diaphragms that restrained sudden surges of gas pressure, which might extinguish flames or cause noise in some types of burners. The governor at the far right used a pellet of soapstone instead of a diaphragm. (D. Chandler, *Outline of History of Lighting by Gas*, 1936.)

Although the batwing burner gave off slightly more light, the fishtail burner was used in most cases because it was desirable to use a glass chimney in order to eliminate the smoke given off when a slight movement of air caused the flame to flicker.

The same principle used in Argand oil lamps was applied in the Argand gas burner, which had a horizontal circle of tube with many perforations around the top (fig. 10.9). Because of the many small flames and the danger of their being extinguished, Argand burners were always enclosed by chimneys. Although it was almost twice as efficient as the batwing burner (in terms of energy radiated as light versus total energy consumed), at the end of the nineteenth century the Argand burner was only slightly more efficient than a good oil lamp.[11]

When electric lighting was in its infancy, it was urgent that gas lighting reach higher levels of illumination in order to meet the challenge of electric lighting. It was not always practical for suppliers to provide a richer gas mixture, so one short-lived invention, the albo-carbon burner, attempted to enrich the gas at the burner. A metal container to be kept filled with naphthalene (a component of coal tar) received the gas pipe, and on its way to the burner the gas took with it the fumes of the naphthalene, providing a richer fuel for the flame. A metal rod extended from the naphthalene container to a point over the flame, conducting some of the flame's heat to the naphthalene so that it would evaporate more readily.[12]

The most effective burner was one that took heat from the end point of the lamp system and returned it to the beginning of the process, a principle that had been used in furnaces for making iron and glass. These regenerative burners had complex methods of placing glass chimneys, ceramic cylinders, or metal tubes so that they were heated by the flames. By sealing off other channels, the air on its way to the flame was forced to pass through the heated passageway. At the same time, there was in most cases a method by which heat from the flame was conducted to the pipe in which the gas approached the flame. With both gas and air preheated, combustion and illumination became more efficient.[13] For a very brief period the regenerative burner staved off early advances of electric arc lighting. Like the arc lamp, the regenerative burner was a cumbersome apparatus and found little application, except for large halls, stores, and streets.

Another means of increasing the light radiating from a flame was based on the incandescent properties of certain materials, the way in which they glowed when heated. By using the heat of a flame, rather than its brilliance, incandescence became the method through which gas lighting was advanced during its last decades. During his experiments in the 1820s with various substances, Goldsworthy Gurney, a physician who came to London to pursue a career in science, discovered that the oxy-hydrogen blowpipe that he had invented produced an intensely white light when the flames played on a mass of solid lime. (Lime is calcium oxide, and the oxides of some elements produce strong light when heated, the intensity of the light increasing as the temperature rises.) From this the limelight was born, but, beyond demonstrations for fellow scientists and visiting nobility, Gurney did little with the discovery.

In 1820 young Thomas Drummond joined the military group charged with completing the ordnance survey of the British Isles. One of the greatest problems of the survey was the foggy and rainy climate of the sur-

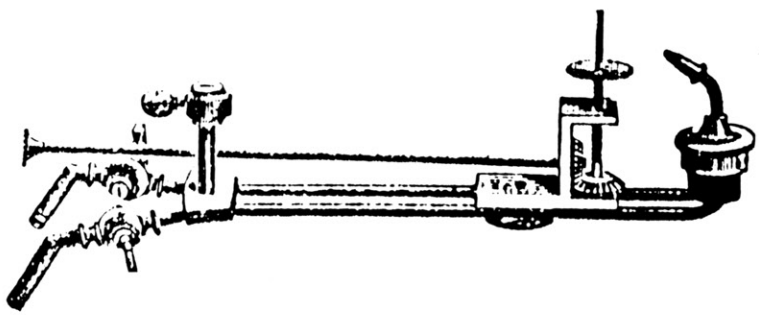
vey area, and this was especially true of the work in Ireland where Drummond went in 1824. To assist in the essential long-distance sighting that established the framework within which detailed cartography was determined, Drummond invented the heliostat, a mirror that pivoted with the sun's movement to maintain a constant beam of reflected light, and from the experiments of Gurney he developed what became known as the limelight or Drummond light. Its intense white glow served well as a target for sighting over long distances through rain and mists. Sir John Herschel, the English astronomer, described a demonstration of the Drummond light:

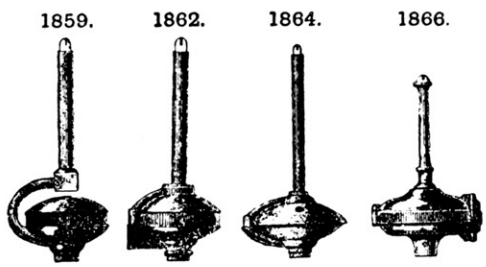
> The common Argand burner and parabolic reflector of a British lighthouse were first exhibited, the room being darkened, and with considerable effect. Fresnel's superb lamp was next disclosed, at whose superior effect the other seemed to dwindle, and showed in a manner quite subordinate. But when the gas began to play, the lime being brought now to its full ignition and the screen suddenly removed, a glare shone forth, overpowering, and as it were annihilating, both its predecessors, which appeared by its side, the one as a feeble gleam which it required attention to see, the other like a mere plate of heated metal. A shout of triumph and of admiration burst from all present.[14]

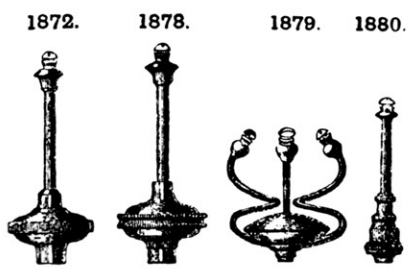
In 1829 Thomas Drummond began development of the limelight for use in lighthouses and concerned himself with methods that might reduce the cost of manufacturing the lights. However, the limelight did not become a commercial enterprise for Drummond because he soon entered into government service and became a leader in the Irish government.

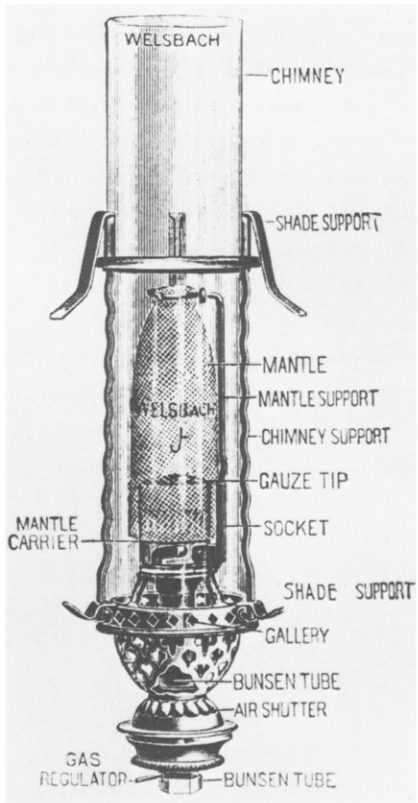
The limelight was often fitted with a reflector and lens to act as a powerful spotlight. It was this form that was employed in theaters to provide a light much stronger than that possible from candles, lanterns, or gas flame (fig. 10.10). (From this use "limelight" came to mean the glare of public attention.) For less spectacular purposes the lamp's white brilliance was not always thought to be desirable. When New York's American Museum on Broadway mounted a Drummond light outside its door, it was described as "sending a livid ghastly glare for a mile up the street."[15]

In the 1860s "Scholl's platinum light perfecter" was introduced and had brief popularity. It was a thin band of platinum that was within a fishtail burner at the point where the two jets of gas met. The brilliantly glowing metal did increase the burner's light, particularly when it was poorly adjusted. However, the perfecter's assistance was appreciable









10.12 At the turn of the century the Welsbach burner had reached this form. A major difficulty was the greenish tint of its light, as compared with the yellowish gas flame and the bluish cast of the electric arc lamp. (*Electrical World and Engineer*, 10 November 1900.)

10.13 An inherent fault of most lamps was that the lamp itself blocked the light from being cast downward, where it was most often needed. This problem was eliminated by the inverted gas mantle lamp, as shown by these diagrams of light distribution. (L. Gaster and J. S. Dow, *Modern Illuminants and Illuminating Engineering*, 1919.)

only when it was new, and in use it soon diminished to insignificance.[16]

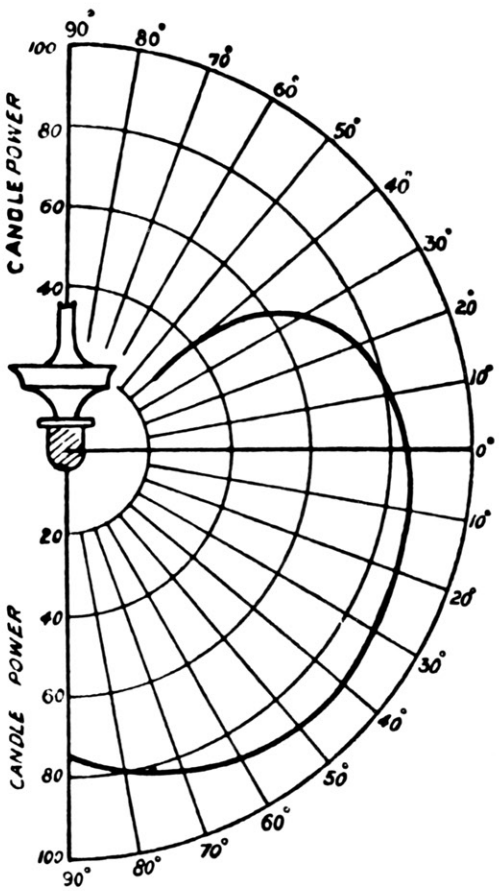
Alexander Cruikshanks in 1839 combined these prior notions and surrounded a gas flame with a mesh of platinum wire coated with lime. Almost a half century later, the next step was taken by Carl Auer von Welsbach, a Heidelberg student of Robert Wilhelm Bunsen, who had studied those oxides of metals that are known as rare earths. Welsbach's invention in its first form was a cotton mesh cylinder that had been soaked in a solution of one of the rare earths (fig. 10.12). The mantle, as it was called, was heated to burn out the organic fibers of the original cotton shape, leaving a delicate shell of mineral substances.[17] Even when placed around the relatively low temperature of a bunsen flame, the mantle produced a brilliant incandescence.

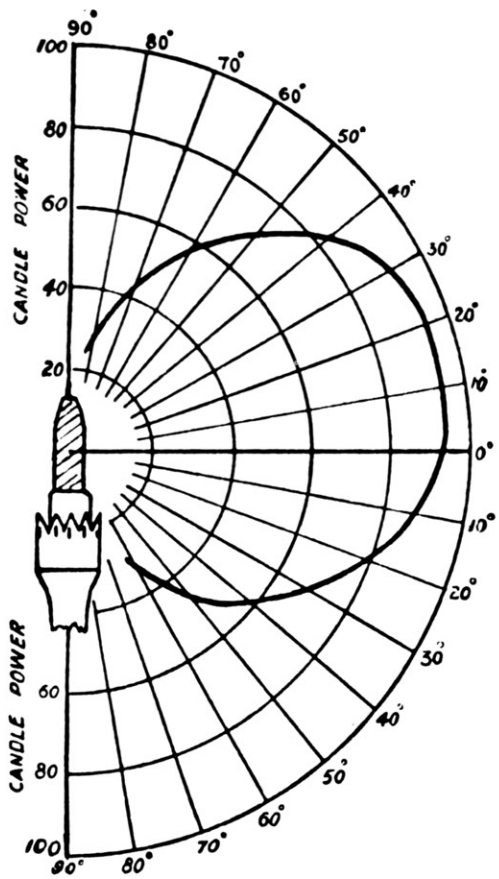
One of the first substances used by Welsbach was erbium oxide, which gave off an unpleasant greenish light. He found a white light was produced by magnesia and the oxides of lanthanum, yttrium, and zirconium, while neodym zircon emitted a yellow light. But these mantles crumbled in a few days. By the time Welsbach took out his second patent in 1886, he had found that a mantle of thorium oxide provided a strong light and a durable mantle, and the addition of very small amounts of cerium altered the green-tinged light of thorium to an acceptable warm white tone. Because early mantles were easily damaged in shipment, they were coated with collodion, which was burned off by the consumer after the mantles were mounted on burners.

Welsbach made extravagant announcements when his first mantles were introduced, but it was 1893 before a commercially plausible mantle was produced. That mantle still required several improvements. Cotton did not have fibers long enough, and short fibers produced fuzzy mantles that burned up rapidly. Ramie, an Asiatic plant also called Indian hemp and Chinese grass, provided longer fibers, and the process of mercerizing, a treatment with caustic soda, increased the strength of ramie fibers. Artificial fibers, made by squirting a cellulose solution through small openings, came to be one of the last solutions.[18] The improvement of the fibers of which mantles were made followed much the same pattern as that of the development of filaments for electric incandescent lamps, experimentation with natural materials leading to methods of fabricating materials to match the requirements of the device.

The Welsbach mantle was developed at about the same time that the electric arc lamp came into use. Jablochkoff's "candles" and Brush's arc lamps had faltering starts and reached maturity in 1893, the year Welsbach introduced the mantle that had resulted from his ten years of trials and errors. The efficiency of electric arc lamps and incandescent gas mantles was roughly the same; both produced light that equaled about 13 percent of the total energy they consumed.[19]

Welsbach's first patent on an incandescent mantle for gas lamps was granted by the German patent office in 1885, and he obtained three related patents in the six years that followed. Once the mixture of 99 percent thorium oxide and 1 percent cerium oxide had been settled on, the manufacture of incandescent mantles became a thriving and competitive industry, for almost anyone who could buy cotton, a knitting machine, and thorium nitrate was prepared to set up business. In several countries, lawsuits were brought against companies that infringed the Welsbach patents. A suit to stop infringement in Germany was decided in 1896 and Welsbach's original 1885 patent was upheld. But that patent did not include the use of thorium oxide, the key ingredient that had been included in a supplementary patent the following year. The portion of the later patent that dealt with thorium oxide was not allowed by the judges of the German Patent Bureau, because use of thoria was not original with Welsbach. Competitors were thus unrestrained by the patent deci-

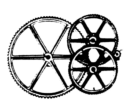




sion, and the manufacturers licensed under Welsbach patents were forced to lower their price drastically in order to meet their competitors' prices.[20]

Welsbach's British patent had been taken out in 1893, but the Welsbach company seems to have been reluctant to test its patent in the courts. At the turn of the century actions for infringement were taken against sellers, not manufacturers, of competing mantles. This delay permitted the organization of a group of competitors willing to share the cost of any litigation that the Welsbach company might initiate, and 27 firms were represented at the initial and exploratory meeting of that group.[21] But this was not the major concern of the Welsbach company. Failing to provide its stockholders with a dividend, the management was investigated by a committee of stockholders in 1902 and judged incompetent. The company was in a precarious state, for only about 15 percent of British gas users employed incandescent mantles.[22]

10.14 Until a satisfactory dry gas meter was devised around the middle of the nineteenth century, meters contained a liquid that sealed the measuring mechanism. Although water was used elsewhere, in the U.S. harsh winters required that the water in a meter be laced with alcohol. Here the installer of meters, carrying his day's supply, is followed by the company representative who filled the meters with alcohol. (L. Stoltz and A. Jamison, *History of the Gas Industry*, 1938.)



Early in the nineteenth century young Humphry Davy was deep in the study of electricity. He gave an account of one of his experiments:

> Pieces of charcoal about one-sixteenth of an inch in diameter whose ends are connected to a source of electric current, are brought near each other (within 1/32 or 1/40 part of an inch), a bright spark is produced, and by withdrawing the points from each other a constant discharge takes place through the air, producing a most brilliant ascending arch of light, broad and conical in form in the middle; hence the term "arch light," commonly called "arc light."[23]

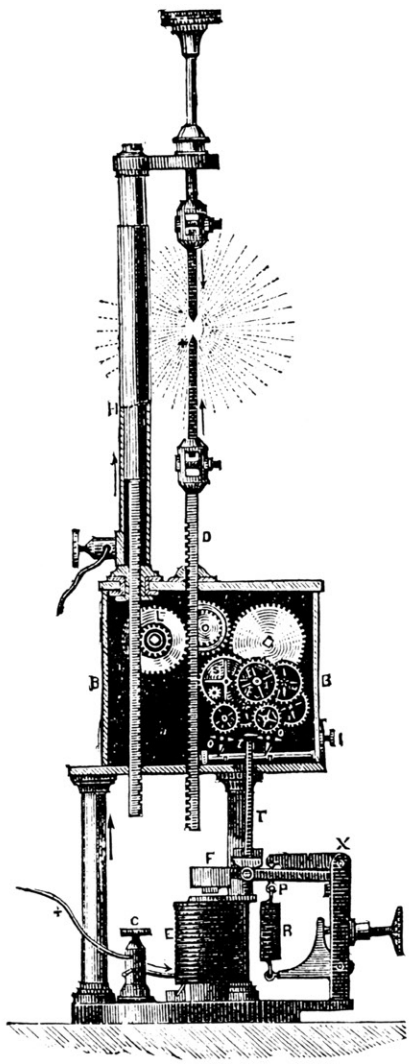
Little was done with this discovery until the 1840s, when Jean Bernard Léon Foucault, a French science journalist and experimenter, replaced Davy's electrodes of wood charcoal with rods made of the carbon from retorts in which illuminating gas was produced. Shaped and baked with syrup as a binder, the hard carbon rods brought a significant improvement in the amount of light produced, but the "arc light" had to be frequently adjusted by hand and was more a laboratory display than commercial competition for the gas burners and oil lamps of the time. All of the arc lamps devised in the middle of the nineteenth century had little practical purpose. The electrodes eroded as the lamp burned, and any durable material for making them had also to be capable of producing large amounts of light. To provide light for a long period of time, it was necessary to find a practical means of maintaining the proper distance between the electrodes, and a system for supplying electric current at lower cost was essential.

Regulation of the electrodes attracted much attention from inventors (fig. 10.15). One design diminished the erosion of electrodes by using two large slabs of carbon so that the arc danced along the narrow foot-long gap between the slabs. Another used five disks of carbon, which were slowly rotated by clockwork. Some inventors adjusted electrodes with the action of springs. Others used weights, clockwork, or magnets. On the whole, the designs were more remarkable for their ingenuity than for practicality. Through the 1850s the more successful arc lamps improved sufficiently to increase the duration of the light in laboratory conditions from 1½ hours to about 12 hours.[24] Arc lamps were installed in a few English and French lighthouses,

and there were uses in the burgeoning field of photography. Still, electricity, which then came from extremely inefficient batteries, was too costly, and the arc lamp mechanisms were far too complex. For over a decade, 1860 to 1872, experimentation with arc lamps was at a virtual standstill. Only after the invention of a practical dynamo did the development of arc lamps resume and progress.

In the 1820s three discoveries opened the way for electricity to become more than a laboratory curiosity. It was found that current flowing through a wire created a magnetic field. Then André Ampère discovered that current in a coil of wire caused magnetic properties, and that when a bar of iron was placed within the coil of wire an electromagnet was created. Within a few years there were experiments to reverse the process, to derive electric current from a magnet. More than 30 years of experiments in electromagnetic induction were required to produce laboratory models of primitive dynamos, and around 1867 several experimenters found methods for using a portion of their machines' output to energize the electromagnets within them. Improvements, principally focused on the methods of winding wires within the mechanism, led to the perfection of a practical dynamo that could supply inexpensive electric power. After 50 years of development and scores of experimental discoveries, the costly current produced chemically in batteries was replaced by electricity from a mechanical source.

In the early 1870s the only significant applications of electricity were telegraphy and electroplating, but the public's rapid acceptance of the telephone soon brought it to a position of leadership among those industries based on the use of electric current. The 1870s saw a revival of interest in arc lamps, and local companies were quickly organized to promote this new method of lighting. Finding an adequate power source was no longer an obstacle, and the principal problem remaining was the means of maintaining the distance between electrodes. In 1876 Paul Jablochkoff, a Russian

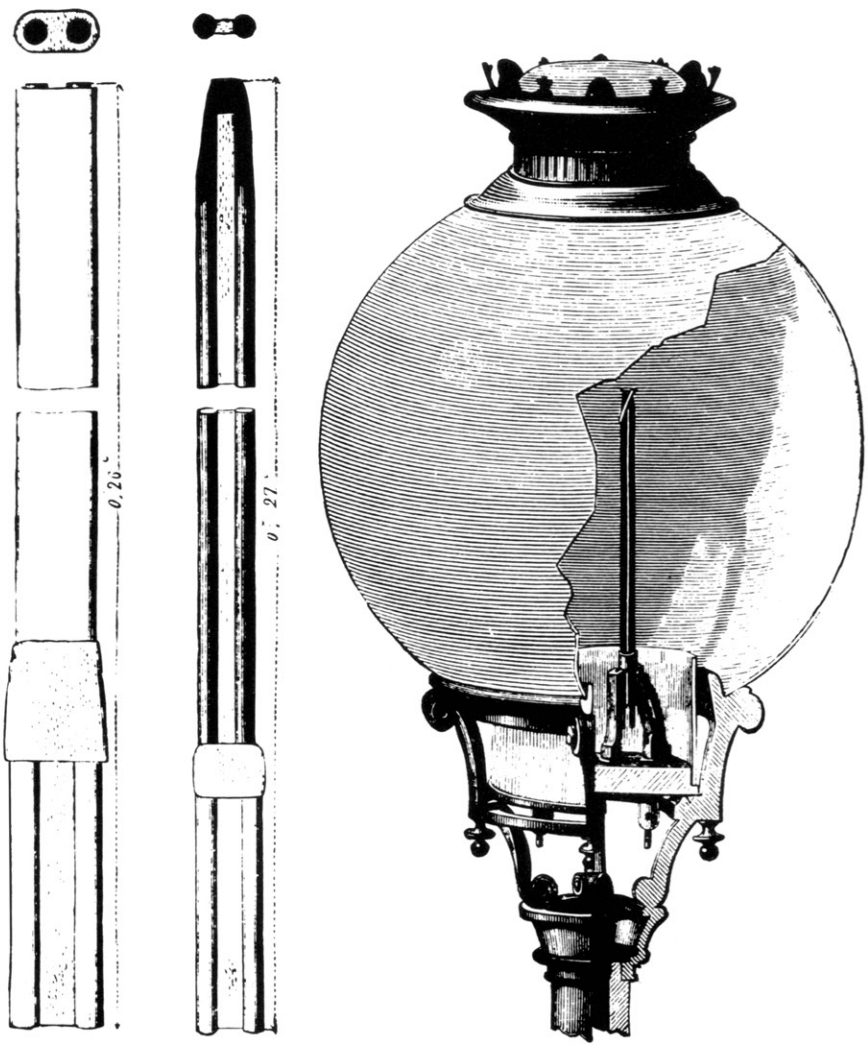


10.15 One of the first mechanizations of the arc lamp was the Foucault Regulator. In order to maintain the desired distance between carbon rods, electromagnetic controls caused the carbons to move closer together when the current carried across the arc decreased, and stopped the movement when the current increased. The movement itself was produced by a spring in the mechanism. (*Appleton's Cyclopedia*, 1880, 1:545.)

10.16 The Jablochkoff candle had plaster or clay between the two rods, which were about 10 inches in length. If the dividing material melted more quickly than the carbons or crumbled, the light became reddish, and carbons had to be replaced every time the light was extinguished. A typical installation of Jablochkoff candles required a steam engine to operate a Gramme dynamo, which provided power for 16 arc lamps. (E. Alglave and J. Boulard, *The Electric Light*, 1884.)

telegraphy engineer living in France, introduced his "electric candle" (fig. 10.16). Instead of arranging carbon rods point to point, he placed them parallel, with a band of ceramic clay or plaster between them. The arc was started by a small piece of carbon between the points. As the carbon rods burned, clay melted or the plaster crumbled, and the arc moved toward the bottom of the candle. The first of Jablochkoff's candles burned for about 1½ hours, giving off an unsteady yellowish light. Two years later he introduced a lamp that would burn through an entire night, six candles connected so that as one burned out, the next was automatically lighted. Standards for street lighting were low at the time; the typical gas burner along downtown thoroughfares provided less light than today's 25-watt bulb.[25] The Jablochkoff arc lamp, many times brighter, was quickly adopted for street lighting in Paris and London. In theaters and large halls the arc lamp did not give off so much heat as gas burners, but its light was harshly brilliant and the arc flickered (fig. 10.17). The Jablochkoff candle made sputtering sounds, wasted much of its light upward, and did not have significant economic advantages over gas lighting. The Reading Room of the British Museum was provided with Jablochkoff candles in 1879, an improvement that doubled the hours during which patrons could use the Reading Room during winter months, but within about 18 months these lamps were replaced by a different design.[26] Seldom did installations of Jablochkoff candles remain more than a few years, usually being supplanted by the complex mechanisms of earlier lamps.

Arc lighting moved from its experimental phase into commercial exploitation with the work of Charles Francis Brush, a graduate mining



engineer and a dealer in iron and steel in the city of Cleveland, Ohio. His contribution began in 1876 with an improved dynamo that could provide current for several arc lamps. The following year he developed a lamp in which differences in the distance between the carbon rods, and the consequent variation of current passing through the arc, caused variation in the amount of current in a solenoid that, in response, repositioned the carbons.[27] The first demonstration of Brush's system took place in Cleveland's Public Square. The lamp was located in a second-story window of the Telegraph Supply and Manufacturing Company and current came from a dynamo about a block away. Brush described the event:

The light was a very small one, of course, but it was concentrated by a parabolic reflector. The occasion was one of a parade

10.17 The brilliance of arc lighting limited its use to locations out of doors and large spaces, such as department stores and factories. This music hall in Paris combined gas chandeliers, Jablochkoff candles in ovoid globes, and mirrored walls and columns. (E. Alglave and J. Boulard, *The Electric Light*, 1884.)

of horsemen and foot soldiers, and all that sort of thing, and the light was thrown in their faces as they came up the street. I remember how the eyes of the horses looked like green balls of light. I do not know how well the horses liked it. They did not seem to care for it very much. After a while a big policeman came up and said, "Put out that damn light!"[28]

A few years later, when Brush lights were first turned on in another Cleveland park, the public brought dark glasses and pieces of smoked glass to protect their eyes from the glare.

The advantage of Brush's work was his attention to the entire system by which light was produced. A Brush lighting plant included the Brush dynamo (which could be operated by a building's steam engine), the arc lamps, and carbon rods that had been copper-plated. The amount and quality of the light produced by the Brush system and others of the period were acceptable for street lighting, railroad stations, department stores, and factories. Wanamaker's department store in Philadelphia installed a Brush plant operating 20 lamps, and a Rhode Island textile mill purchased a system of 80 lamps in 1879, at that time the largest electric lighting plant in the world.[29]

The period from 1873 through 1875 saw a world-wide depression due to excessive speculation, but after it ended practical dynamos were ready at the same time that investment capital was once more available. There followed a startling surge of activity in the development of systems to provide lighting by electricity. The arc lamp gave off little heat, as compared with

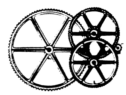
gas lighting, and it provided light more cheaply than other systems available at the time. But a textbook published in 1881 protested: "Its brilliancy is painfully and even dangerously intense, being liable to injure the eyes and produce headaches. Its small size detracts from its illuminating power—*it dazzles rather than illuminates*—and it cannot be produced on a sufficiently small scale for ordinary purpose of convenience. There is no mean between the absence of light and a light of overpowering intensity."[30] The problem of providing small lamps came to be known as the "subdivision of electric light," and arc lamps proved to be incapable of economically producing small amounts of light. As the lamps were made smaller, their efficiency was greatly reduced, and at the same time there was an increase in the cost and inconvenience of replacing carbons and the care required for the mechanisms that positioned the carbons.

Prior to the 1890s, the carbon rods used in arc lamps had not lasted much longer than 7 hours, and for street lighting to last the night it was necessary to provide a second pair of carbons that would light automatically when the first set was finished. Another attempt to increase the duration of arc lamps centered on the composition of the carbon electrodes. Longer and thicker electrodes were tried. Electroplating carbons with a thin coating of copper or zinc was found to increase their life by 25 to 50 percent. A successful device was a metal framework resting on the point of the lower carbon and holding a small tube of fireclay around the point of the upper carbon. By impeding the circulation of air, the fireclay slowed combustion of the carbon.[31]

Through the 1880s many experimenters tried to lengthen the life of carbons by enclosing arc lamps in glass. Their principal problems were the flickering light given off and black deposits that quickly formed on the globes. In the early 1890s several U.S. patents were granted for systems that discovered a simple solution: when carbons were enclosed in a globe that restricted the movement of air, a current smaller than customary would produce a steady light, and carbons would have a life of about 150 hours. In spite of the resistance of lamp trimmers, whose livelihood depended on the short life of carbons used in street lights, enclosed arc lamps soon replaced open arcs. In cities such as Cleveland and Detroit, street lighting was provided by erecting widely spaced towers as tall as 250 feet and raising racks of arc lights as one would run up a flag.

A further improvement came from the development of carbons that replaced the sickly purplish light of the enclosed arc lamp with a yellowish hue rather like firelight. By combining carbon with compounds of magnesium, strontium, fluorine, and other metals, the color of the light was improved. With the electrodes arranged as a V, no shadow obstructed the downward spread of light. The flame arc lamp, as this development was called, had the great advantage of giving off about a fifth the heat of a customary carbon arc lamp, and less than a fiftieth that of equivalent Welsbach gas lights.[32] For each watt of electrical current, the enclosed flame arc lamp gave almost three times as much light as an enclosed lamp of ordinary carbons. A "midget" arc lamp was introduced, but it did not prove to be economical in operation. An enthusiast said in 1911 that "electric lighting by means of powerful sources is inferior to none in the ability to produce tasteful and magnificent effects in immense buildings," but even in the most immense

buildings it was most often recommended that the arc lamps be located between a skylight and a ceiling of ribbed glass.[33] In the show windows of department stores a translucent ceiling was usually set between the arc lamp and the display. Not even the "midget" arc lamp was bearable in a room of ordinary dimensions, and consequently the use of arc lamps remained greatly limited.



A British patent for "Improvements in Obtaining Light by Electricity" was granted in 1845 to Edward Augustin King, the leader of a group of English investors in the experiments of J. W. Starr, a young American working in England. A colleague spoke of Starr as "one of the ablest experimental investigators," but the inventors did little with the invention after Starr's sudden death.[34]

Although the Starr incandescent lamp was an unsuccessful solution, it contained the elements of later designs and confronted the problems that were to trouble others during more than three decades of research that would follow. The incandescent elements described in the patent (elements that glowed when electrical current passed through them) were to be either thin sheets of platinum, a metal of high electrical resistance, or rods of carbon. This incandescent material and the framework that held it were enclosed in a glass tube that had one end sealed. A vacuum (necessary to prevent the incandescent material from being soon consumed by oxidation) was obtained by filling the tube with mercury and inverting it with the open end in a vessel of mercury. Electrical current entered from a copper wire through the mercury and a platinum wire sealed in the glass at the end of the tube. Many of the patent's details were altered as Starr undertook his developmental experiments. Platinum was discarded, and his attention focused on small carbon rods, about ½ inch long and 1/10 of an inch square in cross section. Obtaining and maintaining a vacuum was difficult, for as the temperature rose within the glass container the materials inside gave off gases. Above all, Starr's lamp was a laboratory device and could not be manufactured in quantity and easily installed.

In the design of incandescent electric lamps during the decades that followed Starr's work, the incandescent element was commonly a rod or strip of carbon, although many experimenters used coils of platinum wire. Platinum was expensive, it soon disintegrated when used in air or an imperfect vacuum, and the temperature at which it provided a strong white light was only slightly below its melting point. Iridium had a melting point somewhat higher, but in both cases temperatures were usually kept safely low in order to avoid destruction of the wires. "Lamps with metallic wire filaments were condemned to remain at comparatively low temperatures, emitting light decidedly yellow in color, often looking more like red-hot hairpins than practical artificial light sources."[35] Carbon had a high melting point as well as a high resistance to electrical current. A major problem was carbon's predisposition to vaporize or combine with whatever gases might be present. With imperfect vacuums, carbon elements seldom lasted long, and many designs of lamps made provisions for the replacement of carbon filaments. The extreme case was a Russian lamp, patented in 1875. It contained five carbon rods with provisions for them to be lighted in

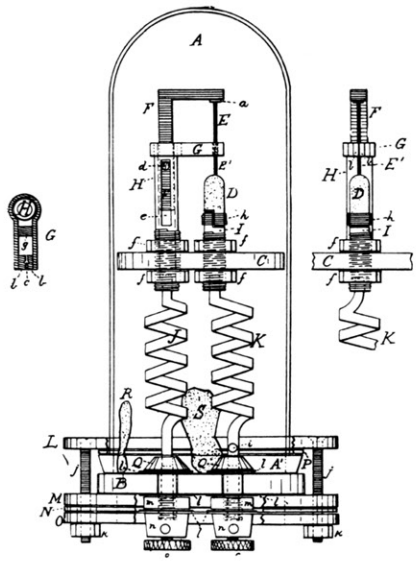
sequence. A description of this lamp said: "The first carbon of a lamp never lasts for less time than a quarter of an hour; sometimes it breaks at the end of thirty to thirty-five minutes, but that is very rarely; its average duration is twenty-one minutes. The succeeding carbons last upon an average for two hours, so long as the luminous intensity does not exceed 40 [gas] burners, in which case the average duration is only half an hour."[36] It was intended that the first carbon would exhaust the oxygen that might be within the lamp, providing a more desirable atmosphere for the succeeding carbons. The automatic series of elements was a method then being used in arc lamps. In fact, it is apparent that much experimentation in incandescent lighting was strongly influenced by practices in arc lighting.

Most of the incandescent lamps invented during this period were the work of experimenters who were largely self-taught in the science of electricity. Progress made in the middle of the nineteenth century can be fairly represented by the work of Moses G. Farmer, a New England schoolmaster, who had left that occupation for a position with a telegraph company. That job he left in 1851 to manufacture an electric fire alarm system he had invented, and as he approached the age of 40 he shifted his attention to the problem of the incandescent lamp. He developed a lamp with a filament of platinum wire and current taken from wet cell batteries, and in 1859 he lighted the parlor of his home in Salem, Massachusetts:

> When we shall see the electric light distributed in our dwellings it may prove a source of pride to Salem to call to mind that this boon met its first success in that city, where a parlor, in Pearl Street, was lighted every evening during the month of July, 1859, by the electric light, and was undoubtedly the first private dwelling house ever lighted by electricity. A galvanic battery furnished the electric current, which was conveyed by conducting wires to the mantelpiece of the parlor, where were located two electric lamps. Either lamp could be lighted at pleasure, or both at once, by simply turning a little button. The light was soft, mild, agreeable to the eye, and more delightful to read or sew by than any light ever seen before. It was discontinued, for the reason that the acids and zinc consumed in the battery made the light cost about four times as much as an equivalent amount of gas light.[37]

Almost a decade later Farmer patented a lamp with a carbon element, and he lighted a residence in Cambridge, Massachusetts, with 40 lamps of this design. He filled the lamp's globe with nitrogen, although he believed that "a vacuum is, perhaps, better, were it not for the difficulty of maintaining it." The repeated heating and cooling of a lamp made most methods of sealing lamp globes unreliable, especially in designs that were stoppered bottles of the sort Farmer used.

The introduction of the Gramme dynamo in the mid-1870s provided a practical source of continuous electric current and stirred new activity in the efforts to develop an incandescent electric lamp. Between March 1878 and the following spring, two similar patents were developed by the team of William E. Sawyer and Albon Man, experimenter and entrepreneur respectively, in their New York shop. The lamp was derived from earlier European designs (fig. 10.18). Electrical current passed through a carbon pencil inside a globe filled with nitrogen, which deterred the deterioration of the carbon. Because the life of such carbon rods was short, a long pencil

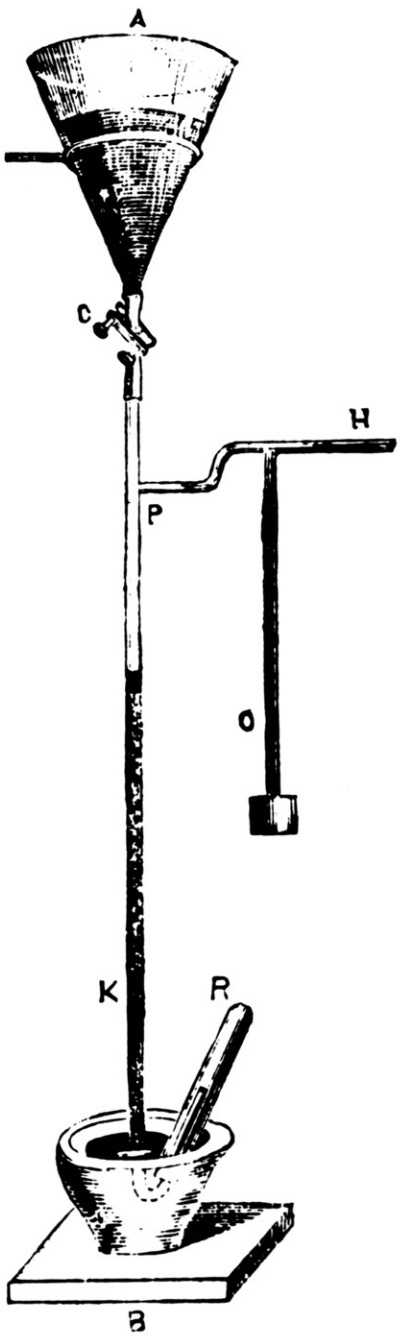


10.18 In the Sawyer-Man incandescent lamp, patented in 1878, light was produced by a carbon rod (*E*). Since the rod did not last long, most of the lamp's upper part was employed to advance the carbon as a portion (*E'*) was consumed. Hollow conductors (*J*, *K*) drew heat into the lower part of the lamp and provided a means of refilling the vessel with nitrogen. Lumps of sodium (*S*) and potassium (*R*) were meant to absorb any traces of oxygen within the lamp. (*Electrical World and Engineer*, 1 December 1900.)

was used and current was passed only through a segment of its length. As the lamp burned, more of the carbon pencil moved into the light-producing portion of the lamp. By having the pressure of the nitrogen about the same as atmospheric pressure outside the globe, it was hoped that the entrance of air could be prevented. In use, however, the heating and cooling of the lamp caused pressure to vary, and air usually entered when the lamp was turned off. After Sawyer was discharged by the company's investors (an action attributed principally to his drunkenness), he started another company, but he seems to have focused his attention more on competition with his former employers than on the improvement of his lamp. The Sawyer-Man Electric Company, organized in 1886, had its name more from the ownership of patent rights than any close association with the inventors, and within two years it was bought by Westinghouse.

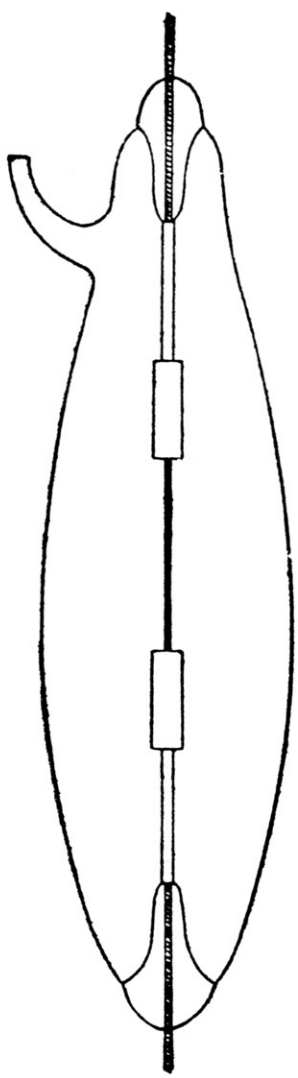
Joseph Swan, an English chemist, experimented with incandescent lamps in the 1860s, but the difficulties arising from imperfectly maintained vacuums caused him to halt his studies of the problem. For several years he shifted his inventive attention to the development of photographic plates and papers. Learning of successes using the Sprengel mercury vacuum pump for other fields of experimentation, Swan resumed his study of the incandescent lamp (fig. 10.20). The lamp that Swan exhibited to the Newcastle-upon-Tyne Chemical Society at the end of 1879 was a sealed glass container, abandoning the notion of replacing incandescent units during the life of the lamp, and it contained a thin carbon rod held between platinum wires. In operation the lamp globe was blackened by vapors until Swan began the practice of passing current through the lamp during the process of pumping out air.

Late in 1878, work on incandescent lighting was begun by Thomas A. Edison, already known as the "Wizard of Menlo Park" for his invention of the mimeograph, phonograph, and numerous telegraphic devices. The first patents of Moses G. Farmer and William Sawyer were dated that same year, but it should be remembered that these designs were in many ways crude and impractical and were rapidly surpassed by Edison's efforts. Within a few months the Edison Electric Light Company was formed, with several major financiers included, and Edison informed the New York press that he had solved the problem of incandescent lighting. The announcement was overly optimistic, for at that time Edison was experimenting with systems and incandescent materials that others had already tested without success. There was, however, a significant difference in Edison's approach to the problem of electric lighting. At the very outset he employed a scientist-mathematician to provide a theoretical point of view (something Edison had not always welcomed)



and, as the first lamps were tested, attention was also directed to generators and means of distributing current. As an experienced inventor, Edison viewed the prospect of an efficient incandescent lamp in relation to an entire system of electrical supply that would create a market for the lamp. He quickly reasoned that lamps needed to have a brilliance about the same as that of gas jets, that if the lamps had high resistance it would reduce the cost of copper wires in the distribution system, and that the choice of filaments depended largely on finding a material that could be heated to incandescence without reaching its melting point.

10.19 Invention of the Sprengel air pump greatly improved the vacuum that experimenters could obtain within their lamp globes. Drops of mercury entered (*A*), rolled down a tube (*C-K*), and took along air in falling to the drain (*B*). In the tube (*H*) a small amount of phosphoric anhydride absorbed any moisture that might be present. The bulb to be evacuated would be fastened at the end of the tube (*H*) along which a barometer (*O*) measured pressure. (*Engineer,* 8 March 1867.)

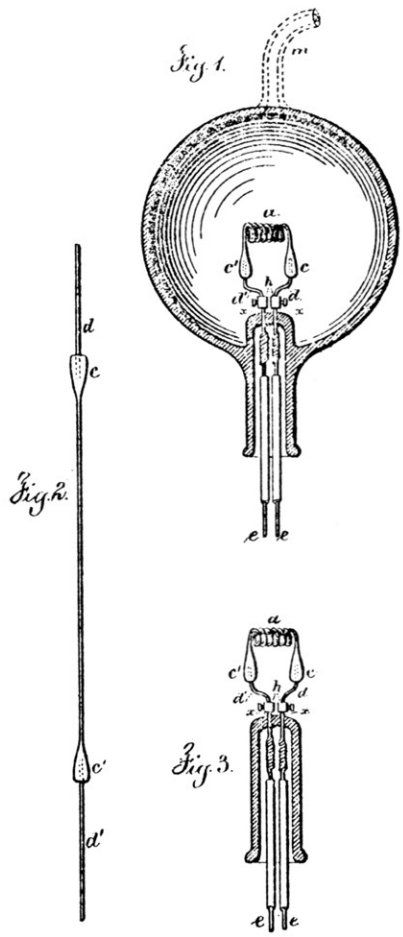


10.20 The lamp displayed by Joseph Swan in 1879 had a thin carbon rod as its incandescent element. Current entered through wires of platinum, the only metal that would not expand and crack the glass. The lamp shone only briefly and deposited carbon particles on the inside surface of the glass. The following year Swan began experimenting with other materials as filaments. (Reprinted with permission of Macmillan Publishing Company from Arthur A. Bright, *The Electric-Lamp Industry.* Copyright 1949 by Macmillan Publishing Company, renewed 1976 by Evelyn F. Hitchcock.)

Early incandescing elements were usually made of platinum or iridium (two metals with high melting points) or carbon (which had a melting point higher than that of any metal). The brightness of the light increased with the temperature of any filament, and it was a relatively narrow range of temperature—between glowing heat and melting—that drew the attention of experimenters. In the 1870s, when enthusiasm for the study of incandescent lighting increased because adequate sources of electrical current became available, and for many years after, carbon filaments were the most satisfactory available.

Carbon filaments were made by cutting fine strips of a cellulose material and slowly subjecting them to high temperatures while in a closed crucible. Hydrogen and oxygen were thus driven from the filaments, leaving a skeleton of carbon, hard and dense like coal. Joseph Swan in 1860 had used carbonized strips of paper and cardboard, and Edison's first commercial lamps had filaments of carbonized paper, but they proved to be too fragile (figs. 10.21, 10.22). Edison had tested a variety of materials (6,000 according to some stores), including monkey grass, jute, coconut palm, and hair from the beards of his laboratory workers.[38] When he tested bamboo in 1880, it produced a filament that was firm and hard. Agents were soon dispatched to the Amazon, China, Japan, and India with instructions to obtain samples of every kind of bamboo they encountered and send them back to New Jersey. A Japanese bamboo, madake, was found to be the best, and it was used by Edison until 1894, although agents continued to travel in search of a variety still better.[39]

In 1894 the General Electric Company began marketing incandescent lamps in the United States with



10.21 In his 1880 patent, Thomas Edison was vague regarding the filament: "I have carbonized and used cotton and linen thread, wood splints, papers coiled in various forms, mixed with tar and kneaded so that the same may be rolled out into wires of various lengths and diameters." The spiral filament shown in the patent proved difficult to make and was succeeded by a simple horseshoe shape. (U.S. Patent no. 223,898.)

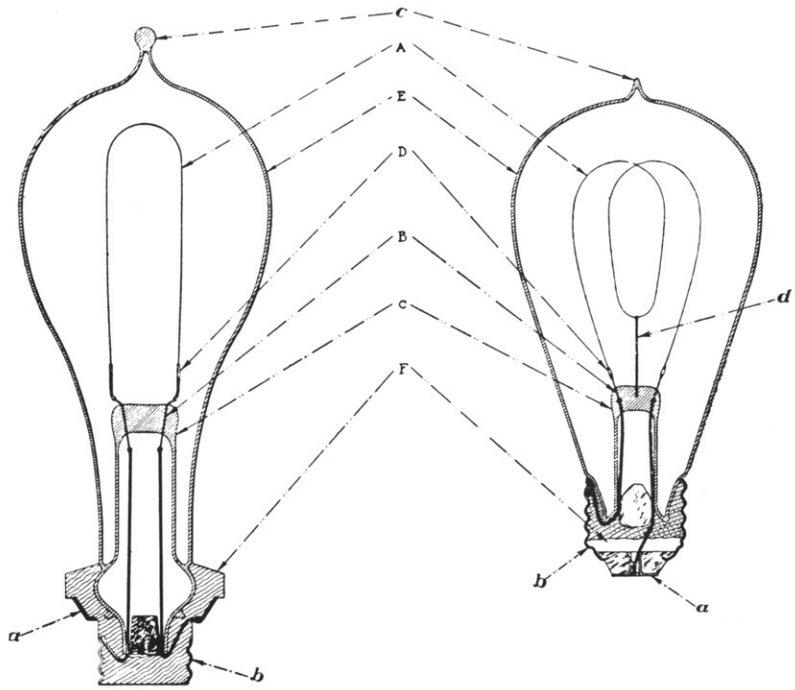
10.22 Between 1881 (left) and 1905 (right), the Edison lamp changed considerably: (*A*) The hairpin of carbonized bamboo gave way to a double loop of carbonized artificial cellulose fiber. (*B*) Platinum lead-in wires were shortened. (*C*) The stem of the glass tube became smaller. (*D*) Copper wire and copper-plating used to secure the filament to lead-in wires were replaced by a carbon paste. (*E*) "Free-blown" bulbs, which varied slightly in size were followed by bulbs that were machine-blown into molds. (*F*) The screw base was simplified and reduced in size. (*Journal of the Franklin Institute*, July 1905.)

"squirt" filaments. These filaments, first used by Swan over a decade earlier, were made by dissolving cotton and squirting the syrupy mixture through a die into alcohol. The threads produced by this process—cellulose, like the materials that had been used previously—were then carbonized, and those filaments were better than any made from bamboo. Carbonized "squirt" filaments became commercially available in incandescent lamps at about the same time that the first "artificial silk" made by a similar process was sold in France.

Platinum and iridium had been found to have melting points too near their temperature of incandescence. Carbon filaments, no matter what form of cellulose had been carbonized, had the disadvantage of containing minute portions of impurities that, when the filament was lit, caused the carbon to vaporize and be deposited on the surface of the glass bulb. Gases were inserted to inhibit vaporization and reduce blackening of the bulb, and "getters" (air-absorbing chemicals) were placed in the lamps to insure a complete vacuum. By 1905 many manufacturers were treating filaments by subjecting them to temperatures much higher than those of the carbonizing process. This method of "metallizing" the carbon filament resulted in improvements of around 25 percent in efficiency, but by that time the development of wire filaments had begun.[40]

The Nernst lamp was introduced in 1897, but its incandescent element was a rod of rare oxides that had to be preheated with an electric coil, a system requiring a wait of almost 15 seconds before the light came on.[41] Welsbach, developer of the gas mantle, experimented with wire filaments of osmium in the same period, but his lamps were so expensive and the filaments so fragile that his lamps were rented rather than sold.

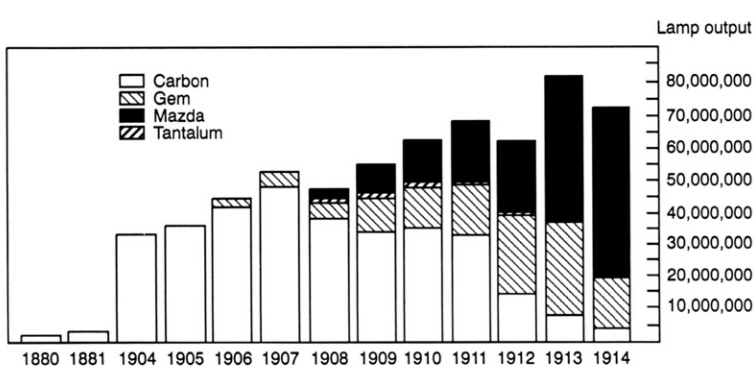
The tungsten filament was introduced commercially in the United States in 1907 after the General Electric Company purchased Austrian patents (fig. 10.23). Tungsten is a plentiful metal, extremely heavy and hard (the name is Swedish for "heavy stone"), with a high melting point and a low electrical resistance that increases as the metal is heated. But tungsten is not ductile, and the early filaments made of the metal were produced by mixing a fine tungsten powder with sugar and gum arabic. This paste was squirted through diamond dies, and those threads were heated to burn away the binding ingredients. Lamps with such filaments were very efficient, but the tungsten wire was fragile. It required several years of concentrated experimentation to find a method by which lamp manufacturers could draw tungsten wire, overcoming the stubborn metal and providing sturdy filaments for incandescent lamps.



After the introduction of the durable ductile tungsten filament of drawn wire, three major improvements were made in the incandescent lamp (fig. 10.25). Even with tungsten filaments, bulbs blackened and efficiency was reduced; almost 95 percent of the electrical energy employed in a vacuum tungsten lamp was squandered in heat.[42] It was found that filling bulbs with nitrogen eliminated blackening

and allowed a higher temperature in the filament, a change that increased a lamp's efficiency. In some cases it was necessary to place a mica disk in the neck of the bulb to prevent overheating the base of the lamp. Frosting of bulbs was recognized as desirable to diffuse the light and eliminate the glare of visible filaments, but it proved difficult to achieve. Opal glass and external frostings were unsatisfactory, and years passed before a method was found to etch the inside of bulbs while retaining the strength of the glass. The remaining improvement was accomplished by altering the form of the filament. If a tungsten filament were tightly twisted into a screw-shaped coil, the heat loss was determined by the diameter of the coil, not the diameter of the wire. In order to further increase the effective diameter, after 1926 the coiled filament was coiled a second time, resulting in the coiled coil or double-coiled filament that reduced heat losses. Drawn wire filaments and these three improvements caused the efficiency of incandescent lamps, as measured in units of light per watt of electrical energy, to roughly double in the period from 1910 to 1940.

Although gas companies and those producing electricity were clearly competing for lighting customers, at first there seemed a possibility that gas and electric lighting might coexist with a reasonable level of profit for both. In 1891 the gas companies of Massachusetts, for instance, produced and sold 20 percent more gas than they had in 1889, and in that same period the state's arc lighting increased by 33 percent and incandescent electric lighting by 117 percent. One writer pointed out in 1892 that "though the world has absorbed in vast amount the new illuminant known as electricity, it does not follow that the use of gas has decreased to a corresponding degree."[43] His argument followed a simple, though fragile, logic. In order to attract customers, stores were lighted electrically above the required levels for visibility, and merchants who grew accustomed to that level of light insisted on as much from gas burners at home. Furthermore, he reasoned, the shadows of skyscrapers darkened the lower stories of buildings nearby and thus created a need for more light. Supporters of each method of illumination published intricate calculations comparing the cost of equal amounts of light as produced from gas and electricity. Some partisan exaggeration must be assumed, but at the turn of the century it is evident that a unit of light was more expensive if provided by electricity than by gas, and the comparative investment in electrical generating equipment was even higher. Since gas-producing plants were in place and electric stations had to be built, investment costs were a decisive factor. One expert in 1900 compared light sources according to the percentage of energy radiated as light (the rest expended as heat); see table 10.1[44] The calculations were even more staggering when the radiated light energy was compared with the energy in a given amount of coal used in its production (table 10.2).[45]



10.23 Electric lamp production in the United States, 1880 to 1914, by number and type, shows the decline of carbon filament lamps with the introduction of Gem (metallized carbon) and Mazda (tungsten) lamps. Between 1907 and 1914 the light produced by a 60-watt Mazda lamp increased almost 30 percent and the price was reduced by about 75 percent. (Redrawn from *Electrical World*, 16 October 1915.)

Table 10.1 Energy Efficiency of Various Light Sources

Light Source	Percent of Energy Emitted as Light
Batwing gas burner	**1.3**
Candle	**1.5**
Oil lamp	**2.0**
Argand gas burner	**2.4**
Incandescent "glow" lamp	**5.0**
Limelight	**9 to 14**
Welsbach gas mantle	**13**
Arc lamp	**13**

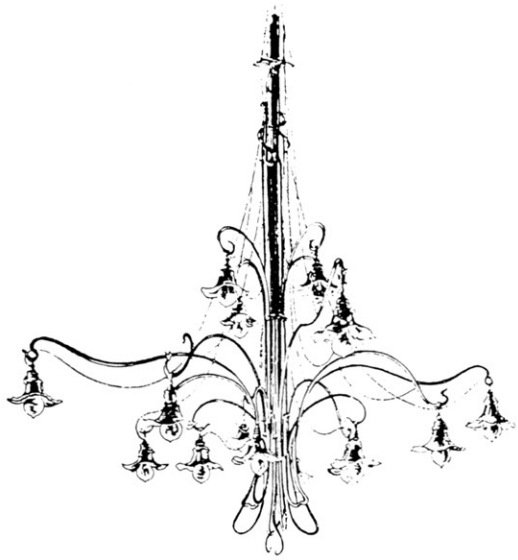
Table 10.2 Energy Efficiency of Various Light Sources

Light Source	Percent of Coal Used as Light Energy
Batwing gas burner	**0.23**
Argand gas burner	**0.43**
Incandescent "glow" lamp	**0.5**
Arc lamp	**1.3**
Welsbach gas mantle	**2.3**

The incandescent gas burner, particularly Welsbach's mantle, gave new hope to the gas industry. At a meeting in England in 1905, the manager of Manchester's city-operated gas plant reported that in his city equal quantities of light were eight times as costly with electricity as with gas.[46] In the same year, stockholders of London's South Metropolitan Gas Company were told that the company's new customers had resulted in less than two-thirds the predicted increase in the amount of gas used, a disappointment attributed to the fact that incandescent gas burners required about two-thirds the amount of gas used by previous burners to provide the same amount of light.[47]

Cost, however, was not the deciding factor. The Victorian desire for comfort and convenience (which favored electricity) was strong among the middle and upper classes, and the lower classes still used lamps and lanterns. In the first decade of the twentieth century, the pneumatic switch for gas lighting was introduced in an effort to gain some of the operational ease to be found in electrical installations. In this device, a push-button sent a surge of air pressure through a tiny metal tube that ran along walls and ceilings to the gas fixture. There the pressure opened a gas valve, and the flame was ignited from a pilot light that was incorporated in the fixture. As late as 1929 a British firm introduced a switch that operated electrically from a small battery that heated a wire until it ignited the gas.

A boost to gas consumption was increased attention to lower-income users. The well-to-do switched to electric lighting, retaining gas as a cooking fuel. The poor kept to coal or oil, which could be purchased in small amounts as money was available. The average workman's life and income were too uncertain to set aside money for quarterly gas bills and a deposit to the company; and their landlords were reluctant to invest in improving the illumination of their properties. Oil for lighting and coal for cooking were the most accessible fuel supplies until the introduction of the penny-in-the-slot gas meter in the 1890s. Coin prepayment meters were tried in London in 1888, but did not succeed until introduced by the Liverpool Gas Company four years later.[48] Eyeing that success, London's South Metropolitan Gas Company again ordered and advertised penny-in-the-slot meters. During a period when that company added 1,063 ordinary customers and 3,654 cooking ranges, it added 17,055 coin-metered customers



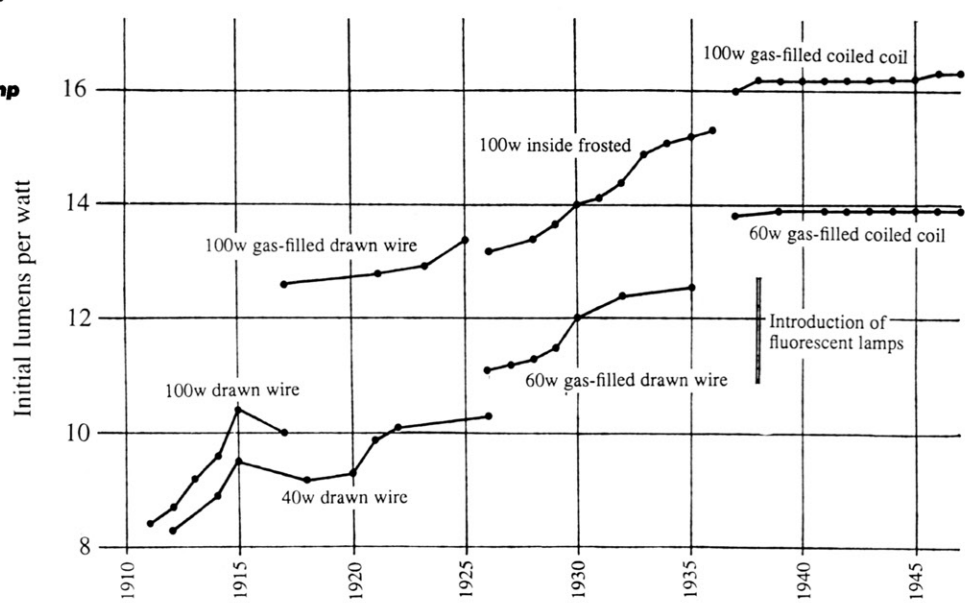
10.24 The transparent glass globes and the wires of electric lighting gave impetus to the development of new fixtures. Art Nouveau designers were particularly inclined to relate the lamps to flowers, as in this Belgian chandelier for a boudoir. (*Art et Décoration*, January 1897.)

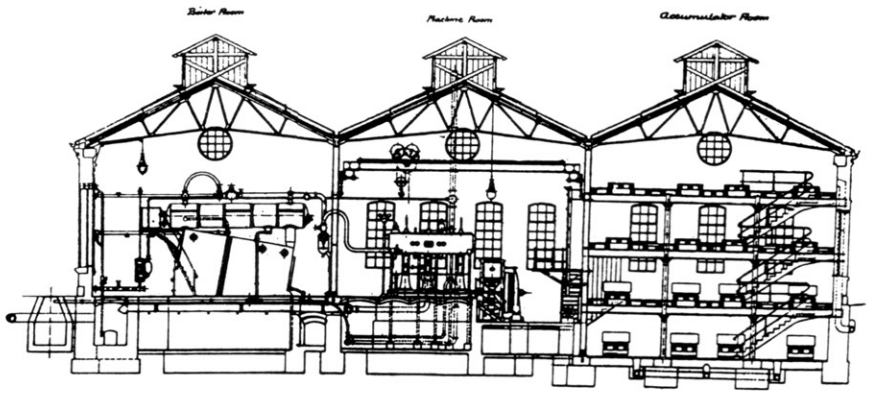
10.25 Improvements in incandescent lamps about doubled their efficiency in the period from 1910 to 1940. However, when introduced in 1938 the 30-watt fluorescent tube had an efficiency of 35 lumens per watt, twice that of the 100-watt incandescent bulb of that time. (Graph developed from data in A. A. Bright, Jr., *The Electric-Lamp Industry*, 1949.)

and 18,865 cooking ranges metered in that manner. In the United States, meters were designed to receive a twenty-five-cent piece, and before World War I they had become at least one-third of the total number of meters installed annually.[49]

The provision of electrical power was obviously a promising investment in the United States. A group of prominent businessmen in Buffalo, New York, in 1887 offered a prize of $100,000 to the inventor who would find a way to make the tremendous force of Niagara Falls work for their city. For this purpose the Niagara Falls Power Company was formed, but in 1889 its stock was purchased by a coalition of New York bankers, who had formed the Cataract Construction Company with the intention of building a hydroelectric project of much larger scope. The Swiss had made turbines of the size needed to harness Niagara, and therefore the generation of power was judged to be feasible. But how should that power be transmitted the 20 miles to Buffalo? This led to the question of whether alternating current or direct current should be used.

Alternating current could easily be raised to high voltage, which was transmitted with much less loss than direct current. Furthermore, alternating current generators and transformers were superior in efficiency to those of a direct current system. From the point of view of producing and transmitting electrical power, alternating current was unquestionably preferable. On the other hand, at that time electric lighting constituted the main use of the power, and therefore the amount of energy to be used fluctuated greatly through the day and night. For a direct current system, a combination of several generators mounted in parallel and a group of storage batteries could compensate for variations in load by operating more generators as loads increased and





10.26 Early direct current electrical plants used accumulators (storage batteries) to supply power when generators were not running. This European plant, built in the 1890s, had three sections (left to right): the boiler room, in which steam was produced; the machine room, in which steam-driven generators supplied electricity; and the accumulator room, in which four levels of lead-acid batteries stored some of the electricity. (K. Hedges, *Continental Electric Light Central Stations*, 1892.)

drawing from batteries during the short period of peak load (fig 10.26).

The "battle of the systems" raged during the period in which the first large generating plants were being built. In England, the Deptford station was in operation in 1891, using alternating current. Debate over the two systems continued among British engineers for many years, and in some areas of England direct current persisted into the 1950s. In the United States the argument was bitter, but its resolution was decisive. Edison advocated the use of direct current and opposed alternating current as presenting a greater danger to the user. George Westinghouse replied angrily in support of alternating current. Because high-voltage transmission was recognized as being advantageous and the technique of constructing high-voltage generators was more firmly established, the contract for the Niagara Falls project was awarded to Westinghouse. Thus alternating current became standard in the United States, but competition continued, much of it focusing on inventions and their patents.[50]

By the end of the eighteenth century, patents were no longer royal prerogatives, monopolies bestowed at the pleasure of the government, but instead had become recognized as rights of the inventors. The U.S. Constitution authorized Congress "to promote the Progress of Science and the useful Arts by securing for limited Times to Authors and Inventors the exclusive Right to their respective Writings and Discoveries." It was assumed that a monopoly for a limited time would serve as an incentive to inventors, afford them a reasonable opportunity to develop production of their inventions, make them known to the public, and reap fitting rewards before they became available for others to manufacture. This monopoly was in some ways contradictory to the antitrust legislation of the late nineteenth century, but both had the objective of increasing and improving the goods available. However, these objectives were often neglected when extensions of patents were granted, additions were recognized, and closely related improvements were patented by others. A common practice—one

10.27 In little more than a decade U.S. manufacture of lighting became concentrated in two giant corporations, although a few smaller companies remained. This diagram shows the development of the Westinghouse Company and the intricate lineage of the General Electric Company. (Reprinted with permission of Macmillan Publishing Company from Arthur A. Bright, *The Electric-Lamp Industry*. Copyright 1949 by Macmillan Publishing Company, renewed 1976 by Evelyn F. Hitchcock.)

used in the case of electric incandescent lamps—involved the owners of major competing patents agreeing to pool their patents. In some cases, the agreements by which other companies were licensed to use those patents included restrictions, limiting production and controlling the retail price at which the product could be sold. There were sometimes, in fact, requirements that any improvements in the product or process patented by licensees should be made available to the entire patent pool. With patents granted for periods from 15 to 20 years, it was possible for the owner of an initial patent to establish a mercantile dominance that could be maintained for several decades. Nevertheless, there was often a reluctance to institute legal action against those who infringed a patent. Pursuit of an infringement case often required exposing details of manufacturing the product, details much more specific than those revealed in the patent. More important, the courts in most countries considered both the evidence of infringement and the validity of the patent itself. Many of the advantages, perils, and frustrations of patent suits are present in the case of Thomas A. Edison's incandescent lamp patent.

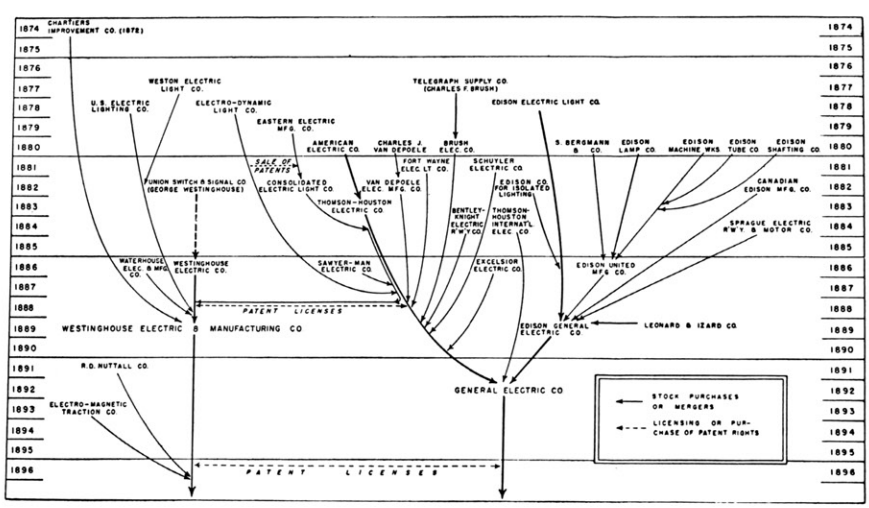
Edison filed application for his major U.S. patent for incandescent lighting (no. 223,898) in early November 1879. It was granted on 27 January 1880, with patents also awarded by Canada, Belgium, Italy, and France between those dates. Many of the problems came from the wording of these patents. The German Supreme Court declared the German patent "extraordinarily obscure"; the English Court of Appeals suspected that the patent it considered was "studiously and willfully obscure." A U.S. judge commented, "The language of the patent itself. That is the greatest cloud that hung over it."[51] In 1882 the Edison Electric Light Company and Swan United Electric Light Company charged each other with infringement of basic British patents. This litigation was settled out of court by a merger of the two firms into the Edison and Swan Electric Light Company, commonly referred to as "Ediswan." In France the clash between Edison and Swan companies was also solved by a merger, producing the Compagnie Générale des Lampes Incandescentes. There was no merger in Germany, the courts deciding in 1891 that the Edison patents were valid but that Swan patents did not infringe.

When the Brush company in 1882 obtained rights for the use of Swan patents in the United States, Edison's company was threatened. The Edison Electric Light Company did not very actively defend its patent rights until after the first five years of the patent's 17-year term had passed. At that time Edison interests may have been encouraged by the German courts' decisions favoring their 1880 patent, but the U.S. patent examiners rejected Edison's efforts to amend his patent. The Edison Electric Light Company in 1885 brought a suit against the U.S. Electric Lighting Company that was used as the test case on the strength of the patent. Edison's lawyers began a delaying action, obtaining 23 continuances. In 1889, four years after the suit had been filed against the U.S. Electric Lighting Company, there was a change in the participants. George Westinghouse, newly interested in electrical goods after developing a company based on his invention of air brakes for railroads, bought the U.S. Lighting Company. When a decision favoring Edison was given in 1891, the latter's company rapidly brought suit against most of the small companies producing incandescent lamps.

Through the six years that remained of the patent's term, the Edison Electric Light Company continued a militant campaign of protecting its patents. The syndicate of financiers that controlled the Edison Electric Company arranged a merger with the Thomson-Houston Electric Company, its principal competitor (fig. 10.27). This new electrical firm, named General Electric Company, brought together the two largest groups of electrical patents. Their hold on the manufacture of electric lamps through the remainder of the patents' terms was so strong that when Westinghouse was given the contract to light the 1893 Columbian Exposition in Chicago, it was necessary quickly to obtain a patent that did not infringe on those held by General Electric.

Ten years before, Edison's Pearl Street Station had begun generating electrical current in New York. The previous year the International Electrical Exhibition and the first International Electrical Congress had been held in Paris. It was time for speculators to get in on the ground floor of a new industry's development. The establishment of electric power companies in the United States followed the patterns that had been established by gas companies and the streetcar investors. Before the Pearl Street Station was constructed, Edison took the precaution of inviting New York city aldermen to Menlo Park and providing them with a lavish buffet brought from Delmonico's fashionable restaurant. In other, smaller cities, a newly organized electrical service company most often had a list of investors that included influential local citizens, who hardly needed to curry the favor of city officials. In 1898 Chicago was the largest city in the United States to have its own electric lighting system, as did 58 other municipalities, but in almost all of these cases, there were also privately owned electric works operating within the city.[52]

In England, authorization of electric works was obtained at the national rather than municipal level. Instead of entertaining aldermen, British speculators invited the leaders of Parliament to dinner before that body acted on the law that was to regulate their company. At that high point of English optimism about investment in electricity, it was proposed that monopolies be granted to private companies for a period of seven years, for it was assumed that within that term a company would have achieved a reasonable return on its initial investment. But the law as finally passed by Par-

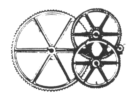


10.28 In 1904 this banking room was lighted with Moore tubes. The tube was 1¾ inches in diameter and 154 feet long, the longest lamp up to that time. (*Cassier's Magazine*, September 1904.)

liament was more cautious, providing a tenure of 21 years for private companies.[53]

With the enthusiasm raised by the Paris and London electrical exhibitions of 1881 and 1882, British investors were anxious to put their money in any form of electrical enterprise. Limits placed on the ownership of power stations by the Electric-Lighting Act of 1882 did not deter these investors, but the major companies' performances caused concern. The Anglo-American Brush Electric Light Corporation, formed to extend the parent company and its system into the British market, licensed many small companies ("Brush babies" as they were called), but it soon became evident that the Brush arc light system was no longer a leader in the field of lighting, and their patent on an incandescent lamp was challenged in courts. By the time the Edison and Swan United Electric Light Company, Ltd., was formed, enthusiasm had waned. In 1883, 69 charters were granted for British central stations and 62 of those were later withdrawn; in 1884 four were granted, all being withdrawn; and in 1885 none were granted. Ten years later the electric industry was referred to as one of "municipal enterprise," and speculation had ended.

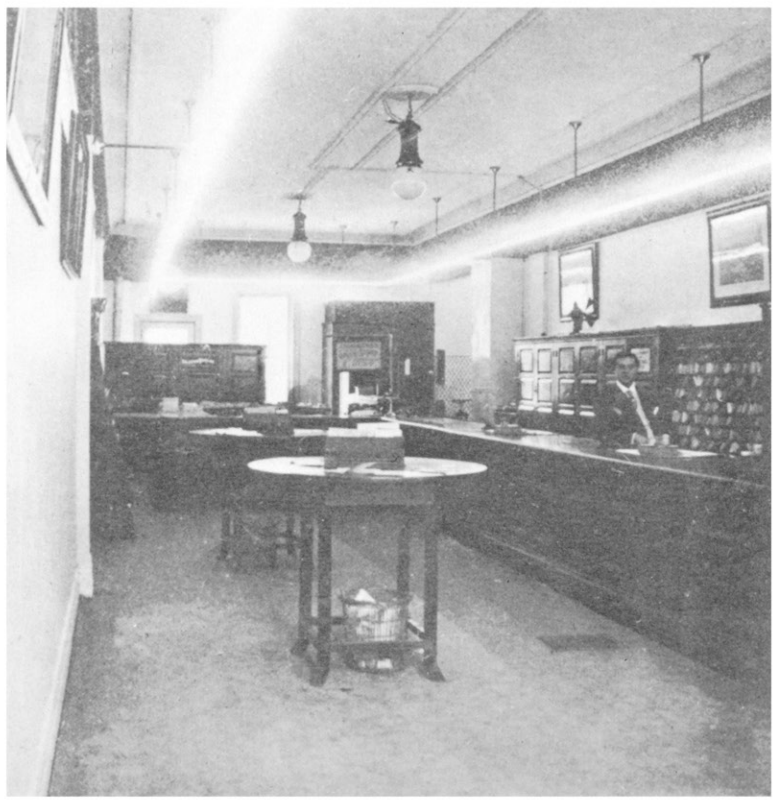
Milan was the first city in continental Europe to build a central station for electric lighting. On the whole, Italian and French cities at the end of the century depended on privately owned power sources and, because few of the significant technological contributions had been made by natives of those countries, the spread of electric lighting was hampered by dependence on the importation of foreign equipment.[54] In Germany, Emil Rathenau purchased patent rights through the Compagnie Continentale Edison in Paris, and with them he established the Deutsche Edison Gesellschaft für angewandte Elektrizität. German cities were divided between municipal ownership and private, although some cities that had built their own plants leased them for operation by private companies.



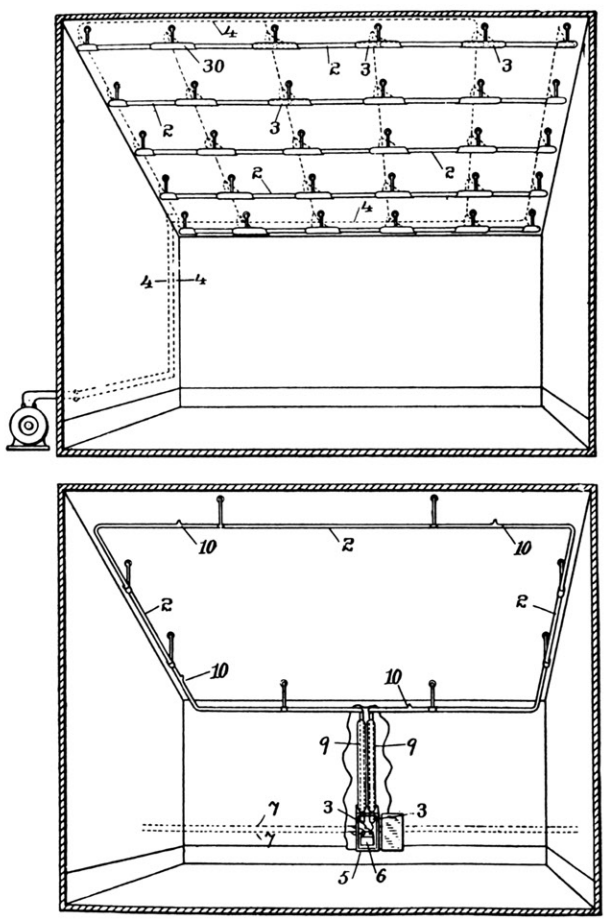
Heinrich Geissler, instrument maker at the University of Bonn, in 1854 fabricated small glass tubes filled with gas that glowed when current was passed through the platinum wires embedded in the ends of the tubes. Little was done to develop the Geissler tube as a light source until the experiments of D. McFarlan Moore. In 1895 Moore exhibited a bulb shaped much like those being used for incandescent filament lamps, but with an arrangement of wires that served as electrodes between which the gas was lighted.[55] By the following year, Moore had concluded that the larger surface area of a tube was necessary to produce sufficient light for commercial purposes. When the tube was filled with nitrogen, a pinkish light was given off; carbon dioxide produced white light, although less efficiently.[56] A major difficulty of the Moore tube was the absorption of gas as the electrodes deteriorated. By using a valve that was electromagnetically activated by decreases in the current in the tube, Moore was able to admit additional gas to the tube.

Although the valve and transformer required for Moore's tube lighting were somewhat cumbersome, reminiscent of the regulators needed for early arc lamps, a tube could be made long enough to light an entire room (figs. 10.28, 10.29). By airtight connections

between lengths of glass, a tube 154 feet long and 1¾ inches in diameter was assembled and suspended around the perimeter of a banking room. The ends of the tube met near the point where a transformer and gas replenishment system were recessed in the wall.[57] Moore's "artificial daylight" was installed in prominent places during the period following 1900. According to studies of the installations at the Savoy Hotel in London and the Palace of Ice in Berlin, the system's consumption of electricity was relatively economical.[58] When displayed in 1905 at the Electrical Show in New York's Madison Square Garden, it was declared to be "absolutely free from glare."[59] Most of the installations were in large rooms, where the glare of arc lamps would be offensive and maintenance of a multitude of small incandescent bulbs was expensive. The major competing lamp using gaseous discharge was the mercury vapor lamp of Peter Cooper Hewitt. The light provided by mercury vapor was lacking in the red portion of the spectrum, a light in which "a person's face looks green and the lips purple."[60] Attempts were made to add other gases in order to correct the color of the mercury light, but they were on the whole unsuccessful (fig. 10.30). Hewitt around 1910 devised a reflector with a coating that fluoresced in a pinkish color, and lamps were made combining the mercury vapor tubes with tungsten filament bulbs in an effort to balance their different hues. In spite of all efforts to ameliorate the inherent characteristics of mercury vapor lighting, the lamps were soon relegated to use in industrial installations and other occasions where large amounts of light were needed and there was little concern for color.



Early in the twentieth century Georges Claude began his work on the production of liquid air while employed by the French branch of the Thomson-Houston Electric Company. In the process of liquefying oxygen he was able to obtain the rare gases, including neon, that had been identified only a decade before. Searching for a light that might equal daylight, Claude experimented with mixtures of helium and neon, trying to balance the blue and red tints of the light produced by these gases in a Geissler tube. This avenue of research proving unproductive, Claude focused his attention on neon, in spite of its red light. The gas's light was dimmed appreciably if only 1 percent of nitrogen were added through deterioration of the electrodes. In an effort to



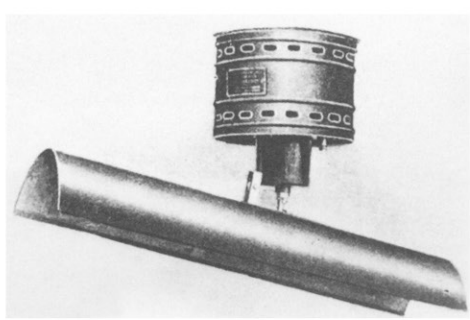
purify the neon, a bulb containing coconut charcoal was attached to the tube.[61] After the tube had been in operation some time and the nitrogen had been absorbed by the charcoal, the glass bulb was sealed off from the tube and removed. Decay of the electrodes was decreased by making them larger, which kept them cooler.[62]

For the Paris Motor Show in 1910, the Grand Palais was "immersed in a sea of bright golden light" from two neon tubes, about 1¾ inches in diameter and each 115 feet long.[63] One of these tubes succeeded in running almost 9 days before being accidentally broken. For advertising or decorative uses, the brilliance and efficiency of neon light proved useful, but few interior spaces could employ light that had little other than the red portions of the spectrum. A mixture of mercury vapor and neon gas had failed in Claude's early experiments, but the mixture of their light could produce a satisfactory color. In 1934 the General Electric Company built a small auditorium to display new lighting equipment in its New York office building. Wanting a general light similar to that of the sun, a combination of lamps was placed in coves around the ceiling: two neon lamps in clear tubes (red) for each two mercury vapor lamps in yellow glass tubes (green) and three mercury vapor lamps in blue tubes (blue). The design of the installation did not smoothly mix the colors, for descriptions comment: "There are areas of color corresponding to the colors of the lamps directly below them and areas of other colors between these, caused by the mingling of adjacent colors, all grading out . . . until they are lost in white near the edges of the ceiling. Then, too, there are varied enlivening colors in all the shadows in the room."[64]

In his book *La Lumière*, Alexandre Edmond Becquerel gave an account in 1867 of his experiments of placing granules of luminescent materials inside Geissler tubes. Although the glow of these materials was far from strong, the Versailles professor proposed obtaining light by coating the inside of a tube with powders. During the remainder of the nineteenth century there were fitful attempts to pursue Becquerel's suggestion. Inventors and scientists, including Thomas Edison and Sir John Ambrose Fleming, tested a broad range of solutions. Fluorescent materials were placed within tubes, on the outside of tubes, and mixed in the glass from which tubes were made. The investigation grew particularly intense at the start of the twentieth century, when D. McFarlan Moore's tubular gaseous discharge lamp and Peter Cooper Hewitt's mercury vapor lamp were introduced. In 1923 a French experimenter coated fluorescent powder on the outside of a tube containing neon and mercury vapor. A few years later he patented a lamp having the fluorescent material on the inside of the tube, but the varnish used to attach the powder produced a vapor that made the lamp's performance unsatisfactory.

European manufacturers around 1930 were much more active in advancing lamps that used mercury vapor, sodium, and neon than were manufacturers in the United States. A trio of German engineers patented a lamp in 1926 that included all of the essentials of the modern fluorescent lamp, but it was not pursued commercially. Although General Electric and the Westinghouse Corporation, virtually controlling the electric lamp industry in the United States, had conducted desultory investigations of fluorescent lighting before World War I, both manufacturers accepted incandescent lighting as completely satisfactory for general purposes of illumination and viewed gaseous-discharge and fluorescent lamps as suitable only for specialized functions. Then in 1933 General Electric's manager of development and engineering for its lamp department returned from Paris, where he had seen installations using fluorescent coatings on tubing much like that employed in neon lighting. His interest was increased the following year by a report from Arthur Compton, a recent winner of the Nobel prize for physics and a consultant for General Electric, who had seen cold-cathode fluorescent lighting in England and was convinced that it was a most promising direction for development. General Electric then began a rapid study of fluorescent lighting.

European installations of fluorescent lighting had concentrated on the use of long tubes custom-bent to suit the requirements peculiar to each installation. Because General Electric's production centered on broad marketing of mass-produced and standardized lamps, it was necessary to find ways in which the custom-made fixtures of European practice could be adapted to the characteristics of industry in the United States. Electric current in Europe was commonly distributed at voltages as high as twice the 110 volts used in the United States; work therefore began on the study of low-voltage fluorescent lights. General Electric's research budget for fluorescent lamps increased from a



10.29 After about six years of exhibiting tube lighting, D. McFarlan Moore received his definitive patents in 1902. Patent drawings indicated two patterns of installation. In one, the tube was shown as a continuous line suspended at the perimeter of the room; in the other, short tubes were connected in a pattern strongly resembling today's installations. (*Electrical World and Engineer*, 28 June 1902.)

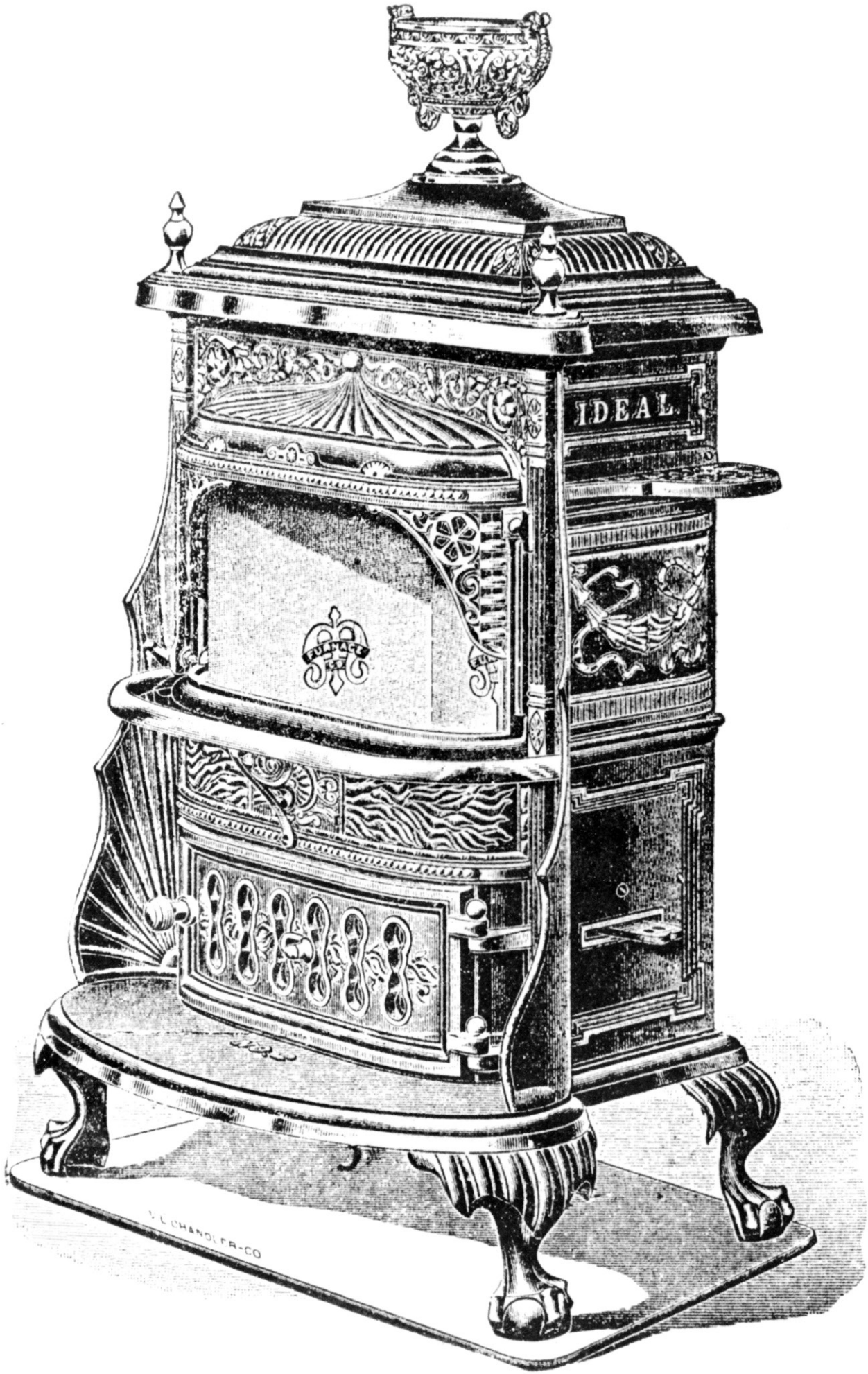
10.30 The unpleasant colors of early mercury vapor lamps led to several years of unsuccessful experiments adding various gases to the tube and metals to the mercury. A brief trial by Peter Cooper Hewitt combined his mercury vapor lamp with a reflector above the tube. The reflector was coated with rhodamine or some other fluorescent dye that would be activated by the lamp and provide light in the red portion of the spectrum. (L. Gaster and J. S. Dow, *Modern Illuminants and Illuminating Engineering*, 1919.)

few hundred dollars in 1934 to $13,400 in the following year, and in two more years it was five times that amount.[65]

Westinghouse joined in the research. For three years the engineers of General Electric labored on the development of the standard low-voltage fluorescent lamp. Since the two companies cooperating in the research dominated the U.S. market in incandescent lamps, their research was both rapid and cautious. A new form of general illumination, especially one that required a different kind of fixture, could prosper only through replacing incandescent installations, new or existing. Commercial failure of the new fluorescent lamps could result in General Electric's losing a portion of its market in the sale of electric lamps. Sylvania Electrical Products, a minor participant in the market-sharing agreement that controlled incandescent lamp production, was developing its own patents for fluorescent lighting. Limited to about 5 percent of the market for incandescent lamps, Sylvania was freer to compete in the field of fluorescent lighting. It was expected that the introduction of fluorescent lighting would rapidly result in large sales. The new lighting was economical; the color of its light approached white; the large surface area of fluorescent tubes reduced glare problems; and the tubes generated less heat than incandescent lamps—a consideration that was to grow in significance with the increased use of air conditioning.

But caution soon had to be abandoned. The New York World's Fair and the Golden Gate International Exposition in San Francisco were to open in 1939. Designers and illumination engineers occupied with planning the buildings for both fairs were aware that the new method of lighting was near introduction. They made it known that they would employ European high-voltage custom-made lighting if low-voltage fluorescent lamps were not available for use in the fairs. Despite their plans to introduce the new lamps over a period of several years, General Electric and Westinghouse were forced to provide fluorescent lamps for the two fairs. The first year's production was mostly used for the two fairs, but in 1938 the two manufacturers listed fluorescent lamps in their catalogs. Four years later 33,600,000 fluorescent lamps were sold. In the first five years in which fluorescent lighting was on sale, the system was more often installed to raise the level of lighting than to reduce the amount of electricity consumed.[66]

In a modern office building about 40 percent of the cooling load for air conditioning results from the lighting system, and for other types of buildings the percentage may be about half that. Although the efficiency of fluorescent lamps has almost doubled since their introduction, less than a fifth of the energy used goes into light (still this is about twice as efficient as incandescent lighting). By current techniques the heat produced by lighting can be used as part of a building's heating system, but nevertheless heating by lamps is not the most efficient method and artificial lighting is most needed in those areas of a building needing the least heating. From the days of gas burners, illumination has always been hampered by its dependence on a form of heating as the source of light, whether oil, gas, or electric current.



Technics and Architecture

The Development of Materials and Systems for Building

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11 Heating and Ventilation

1713 Ventilating fireplaces described in *Mécanique du feu* by Nicolas Gauger

1740 Benjamin Franklin designs an open-front firebox, the "Pennsylvania Fire-Place"

1796 Count Rumford (Benjamin Thompson) advances methods for improving fireplaces

1802 Steam heating installed in textile mill by Boulton and Watt

1806 The Derby Infirmary provided with William Strutt's improvement on the cockle stove

1830 Hot-water radiators installed by Joseph Bramah in Westminster Hospital, London

1830s Three complex stoves installed in the Long Room of the London Custom House

1833 Base-burner stove patented (U.S.) by Eliphalet Nott, president of Union College, Schenectady, New York

1839 David Boswell Reid chosen to plan heating and ventilation of the Houses of Parliament, London

1840–42 Pentonville Prison, London combines hot-air heating with extreme security requirements

1854 Reid's system for St. George's Hall, Liverpool, completed

1859–90 Theories of ventilation propose that specific gases are associated with certain diseases or that organic poisons are exhaled into the air

1876–89 Construction of Johns Hopkins Hospital, Baltimore, Maryland

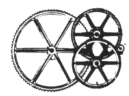
1877 District heating introduced by Birdsill Holly in Lockport, New York

11.1 To construct Benjamin Franklin's "Pennsylvania Fire-Place" one assembled the iron plates shown in this drawing to achieve the stove shown at the lower left. The ribbed plates (upper right) provide the channels at the back through which air circulated as it was heated. (B. Franklin, *An Account of the Newly Invented Pennsylvanian Fireplace*, 1744.)

The ancient Romans had two systems of heating. For public baths after the first century B.C., for villas of the wealthy, and for some public buildings, heat was provided by hypocausts, systems of flues built within floors and walls through which passed the exhaust gases from furnaces. For other buildings braziers of charcoal were customary. At home on a chilly day, when the braziers did not suffice, they put on additional clothing or perhaps left for the nearest public bath.

In parts of Italy a central hearth was the usual source of heat until around 1400, when "French-style" wall fireplaces were adopted.[1] In France, fireplaces might be expected in certain rooms of the finer houses and braziers were carried into others. A French writer in the fifteenth century reported: "For the cold that comes to Germany in the winter they have stoves that heat in such a way that they are warm in their rooms, and in winter craftsmen do their work and keep their wives and children there and it takes very little wood to heat them."[2] Stoves were considered so much a German device that a French king, wishing them installed in his castles, found German workmen to perform the task.

When fires stood against walls, hoods were built over them and flues provided. The only fire in an English manor house of the sixteenth century might be in the central hall, sometimes then referred to as the "fire-house," although another would be provided if there were a separate kitchen.[3] The hood was high enough to permit a cook's stepping under it to tend a spit or stir a pot, and these early fireplaces functioned more as heated alcoves then as heating mechanisms. Almost all the air that was warmed went up the chimney, and fewer people clustered around the fire than could when it stood in the center of the hall. Air that left the room was replaced through cracks around windows and doors, and the latter were often provided with a vestibule of curtains or screens to divert the cold drafts entering.



At the start of the nineteenth century, home life in the United States centered about the fireplace:

> Wood was cheap and labor scarce; therefore the fireplace was made capacious enough to contain a large backlog which lay in the ashes at the rear, and in front of which was the forestick, resting on andirons. The space between these two logs was filled with smaller wood. The living-room in which this fireplace was located served for both kitchen and dining-room, and at night high-backed settees were arranged in front of the fire to intercept the heat, and prevent cold draughts from behind.[4]

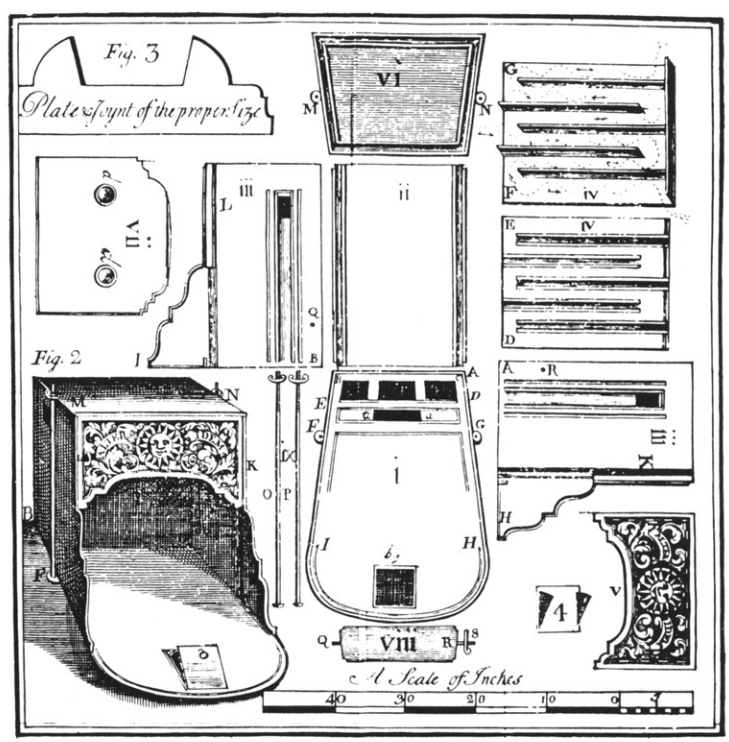
The area that could be heated by such fireplaces had been increased early in the eighteenth century by use of the jamb stove, a box made of five iron plates that was set in the rear wall of the fireplace and extended into the room behind it. Coals from the fireplace were shoveled into the jamb stove and ashes could be removed by raking them forward into the fireplace.

When a larger number of fireplaces were included in dwellings, they were smaller and remained equally inefficient. The problem was one of finding a way to evacuate smoke and gases without drawing too much air from the room or restricting the radiant intensity of the flames and the mass of the fireplace itself. In addition, downdrafts and sooty rooms were to be

avoided. By the seventeenth century, attention was more sharply directed to problems of heating because of the soaring cost of fuel. Fireplace openings and flues were made somewhat narrower so that the rising gases moved faster and downdrafts were less likely. A Paris physician, Louis Savot, noticed a fireplace in a library of the Louvre, and the principle he observed came to be the basis for a profusion of designs after it was published in 1685.[5] The fire was built on an iron plate a few inches above the floor, and behind it was another iron plate with space left between it and the wall. Air was admitted between the floor and the bottom iron plate, and it rose between the wall and the hot surface of the back plate. This hot air was carried by tubes to the front of the mantel, where it returned to the room. The air required for combustion was completely separated from the air utilized for heating. A method had been found to capture and utilize additional heat from the fire by circulating air around the metal plates that held the flames.

A more complete study of the ventilating fireplace was presented in a book, *La mécanique du feu*, published in 1713 by Nicolas Gauger.[6] In Gauger's design of an improved fireplace, the sides were shaped in parabolic curves intended to reflect heat straight out into the room, a subtlety of questionable value. The dimensions of the flue were much smaller than was the usual practice at that time; in fact, they were nearly the dimensions common two centuries later. Fresh air drawn from outside the building was brought into the space between the iron walls of the firebox and the masonry walls of the building, baffles causing it to make several trips up and down before being released into the room. John Theophilus Desaguliers converted the design to the use of coal, at that time the most economical fuel in Britain, and a number of such installations were made in London until they were condemned by some scientists who claimed that such fireplaces "burnt the air, and that burnt air was fatal to animal life."[7]

Early in 1740 Benjamin Franklin designed an open-front cast-iron firebox.[8] His "Pennsylvania Fire-Place" was meant to stand well forward in an existing fireplace (fig. 11.1). Between the plates of cast iron, smoke and heat rose against the front surface of the "air-box," descended along its back surface, and from there rose to the chimney. Within the "air-box" fresh air from a channel beneath the floor passed through a maze of passages before entering the room. In the first half of the nineteenth century there were at least seventeen U.S. patents with titles that included the term "Franklin Stove," and descriptions of the "Pennsylvania Fire-Place" found their way to most European countries. Franklin did not patent his design, preferring to make the stove available



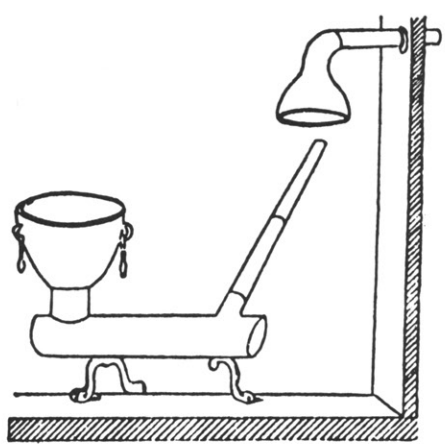
to all without payment of royalties, and he criticized others for wishing to profit from people's need for heat.

It was recognized that the smoke leaving chimneys and falling over sooty cities was unburned fuel. French and German experiments late in the seventeenth century developed cast-iron machines shaped very much like tobacco smoking pipes (fig. 11.2). By establishing a downdraft through the fire, smoke and gases were drawn through the glowing coals, where the gases were burned to release additional heat. Franklin's later "Pennsylvania Stove," an urn-shaped stove, was a more advanced form of downdraft heater.[9] His improvement consisted of channels at the bottom through which the hot gases meandered before entering the flue.

Some of the most intensive studies of heat-producing systems were conducted by Count Rumford, born Benjamin Thompson in Massachusetts.[10] A Tory spy during the American Revolution and knighted by George III, Thompson pursued much of his scientific work in Munich, where he was made Count Rumford by the Elector of Bavaria and was assigned duties that afforded an opportunity to apply his theories to the practical problems of heating and cooking for army barracks, prisons, and institutions that cared for the sick and poor. Rumford's improvement of institutional cooking facilities focused on the elimination of waste. Fires were insulated and served individual cooking utensils that were fitted into the heated mass of the range, eliminating the vast amount of heat that escaped around pots set on open flames. Rumford's fireplace improvements, proposed in 1796, were equally frugal and included practical methods for reshaping existing fireplaces (fig. 11.3). Rumford recommended that flues be narrowed above the fire, providing a "smoke shelf" (a ledge that discouraged downdrafts) at the base of the flue and leaving an opening only about 4 inches deep at the front of the flue. The width of the opening to the flue was allowed to vary according to the size of the fire or fireplace. The fire itself Rumford set well forward in a shallow recess with angled side walls.

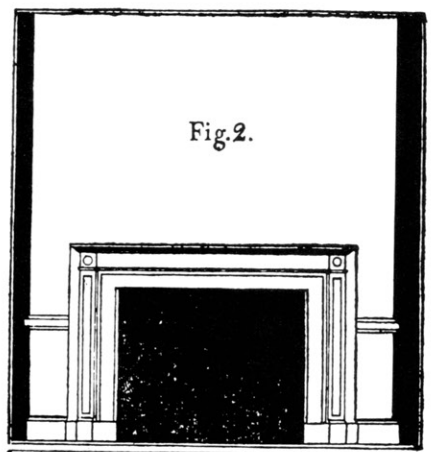
Many fireplaces, particularly in England, were "Rumfordized," the most common complaints being that they provided too much heat after the alterations had been made. Some opponents pointed out that the separate elements of the Rumford design had been previously proposed by others. His scheme was so practical, requiring little more than a mason's filling portions of an existing fireplace, that there was great resentment among manufacturers who had flourished on the sale of cast-iron fireboxes. It was not long, however, before iron founders began to cast new fireboxes that followed the principles of Count Rumford.[11]

During the first half of the nineteenth century there appeared a number of inventions aimed at eliminating the frequent task of feeding fuel to fires. All were curious and a few became popular. By placing enough coal for a full day's heat in a box beneath or beside the fire, these mechanisms allowed the householder to



11.2 By establishing a downdraft, Leutmann's "Vulcanus Famulans," a so-called "smoke-consuming" stove, burned gases and unconsumed fuel that would otherwise have gone up the chimney. A description in 1681 stated that "matters which stink abominably when taken out of the fire, in this engine make no ill scent, neither do red herrings broiled thereon." (J. P. Putnam, *The Open Fireplace in All Ages*, 1882.)

11.3 The process of Rumfordizing fireplaces was essentially a matter of decreasing dimensions. A fireplace of the usual construction (figures 1 and 2) would have its front opening reduced and its back wall brought forward (figures 3 and 4). At the bottom of the chimney, these alterations would result in a smoke shelf and a much smaller opening into the chimney. (Count Rumford, *Essay IV, Of Chimney Fire-places*, 1797.)



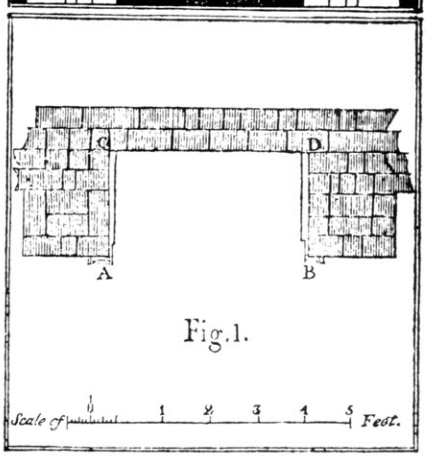


Fig.1.

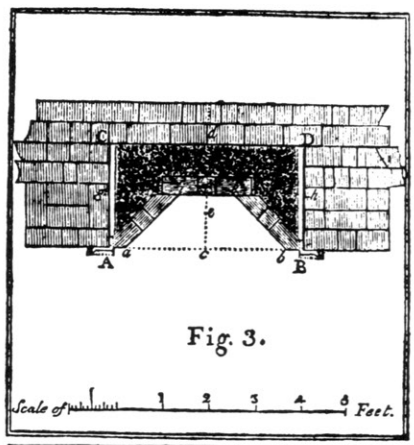
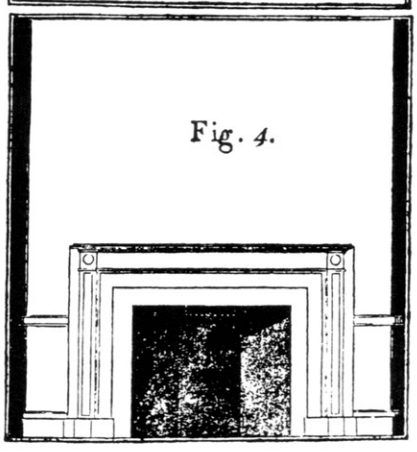


Fig. 3.



feed the fire periodically by manipulating levers, pistons, or plates that separated flames from the fuel supply.

In Europe, stoves were more often used in the northern countries, where large heaters were made of ceramic materials or metal and contained zigzagging flues and interconnected chambers that slowed the burning of fuel and made certain that additional heat was extracted from gases as they escaped to the chimney. The English, however, clung to their fireplaces, accepting only an occasional use of open-front cast-iron boxes as sources of heat for entrance halls. It was in the United States that stoves flourished and went through many transformations.

Most stoves stood out from a wall so that air could circulate and be warmed at all their surfaces, but the stovepipe between the fire and the flue was almost as effective as a heater. A study made early in the nineteenth century measured the duration of heat when different stoves were used to produce a fixed temperature with equal amounts of fuel (table 11.1)[12]

11.4 By the late nineteenth century, circulating fireplaces were commonly available. Ornate grilles above the mantel released air into the room after it had been heated by the metal firebox and the "distributor," a network of flue pipes. In England the grille was usually placed high enough to avoid interfering with the tradition of gentlemen warming their rumps before the grate. (J. P. Putnam, *The Open Fireplace in All Ages*, 1882.)

11.5 At each end of the Long Room of the London Custom House there stood a square stove almost 12 feet high. Smoke was exhausted through a flue (c) beneath the stove. Air was heated by circulating through 22 vertical tubes (*b*). An additional stove, circular in shape, was situated in the center of the Long Room, and its flue carried smoke upward through the ceiling. (*Transactions, Royal Institute of British Architects*, 1842.)

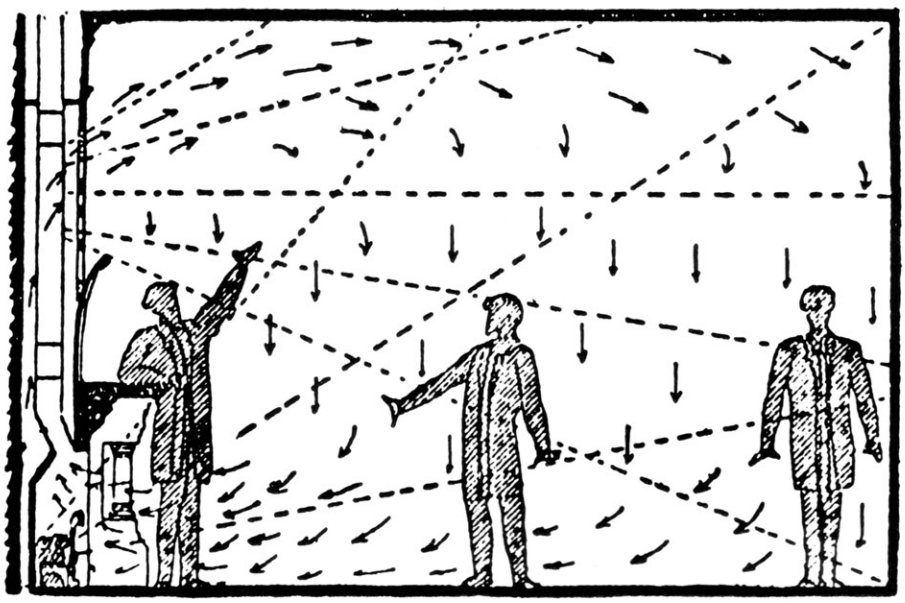
Table 11.1 Duration of Heat for Various Stoves (see text)

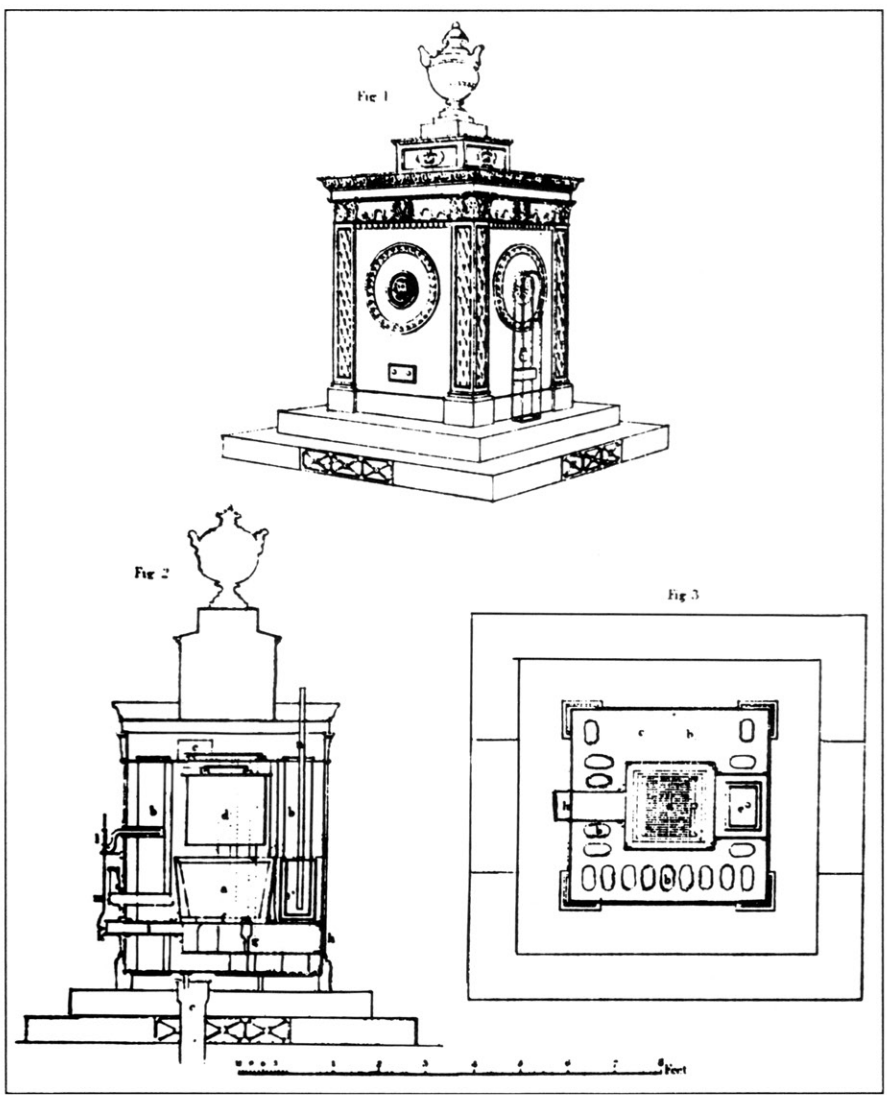
Ordinary fireplace constructed for burning wood	**10 hours**
Open parlor grate for anthracite coal	**18 hours**
Open Franklin stove	**37 hours**
Sheet iron cylinder stove with 5 feet of horizontal flue pipe	**67 hours**
Ditto, with 42 feet of flue pipe having 17 elbow joints	**100 hours**

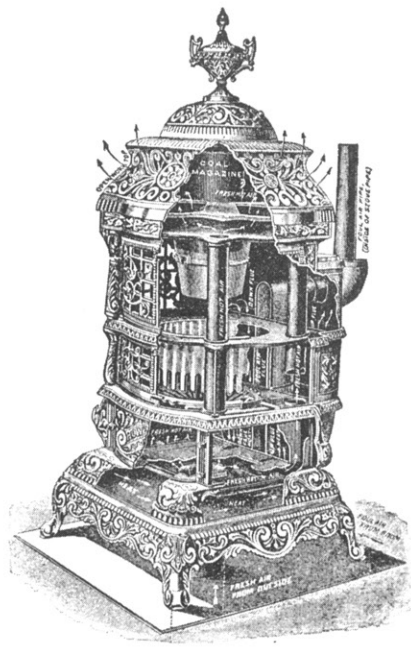
Obviously, a slow-burning stove with a large amount of heated surface was most efficient in supplying heat, and this was the goal of later inventions.

The heating system devised in the 1830s by Dr. Neil Arnott, a London physician, for the Long Room of the London Custom House consisted of three stoves set within the room, but the total organization of the system introduced several of the elements developed further in later heating designs (fig. 11.5). The Long Room was 186 feet in length, 64 feet wide, and 44 feet high, and it provided work space for 130 officials and clerks who served the many merchants doing business there.[13] Additional sashes were placed over the 1,100 square feet of windows in the room, but a skylight of almost the same area seems to have been too difficult to cover. Arnott spaced three stoves in the room, two cubical in shape with descending flues, one a center stove, circular with a flue through the ceiling. Between each stove and its jacket 22 elliptical tubes, in cross section roughly 10 inches by 6 inches, circulated air upward from a space beneath the stove's platform. A tank within the jacket held water, which was reported to have evaporated at a rate of about eight gallons per day for each stove. At that time heat was usually controlled by regulation of the openings through which hot air was delivered, a method that wasted fuel as the fire continued to burn. Arnott's stove had a tube of mercury extending into the space through which air circulated, and a float at the opposite end of the tube regulated the entry of air to the fire according to the expansion of the mercury. The lid of the firebox was sealed to prevent leakage of gas by fitting its edge into a groove filled with fine sand. Stoves they were called, but many elements of a first-class warm-air system were embodied in the design.

Downdraft stoves in the Bank of England had been removed in 1787 as a result of workers' complaints, and there were many objections to those placed in the Custom House. Customs officials declared that air from the stoves caused "a sense of tension or fulness in the head, throbbing of the temples and vertigo, followed not infrequently by a confusion of ideas."[14] Stoves were popular in the United States, where stovemakers entered into intense competition with names such as "Morning Glory," "America," and "Oriental" for their products. Patents for stoves in the United States reached their highest number during the 1830s and 1840s. Cast iron, sheet metal, and soapstone were the more common materials, and coal-burning stoves were sometimes lined with brick to avoid excessive temperatures on their surfaces. Enameled metal permitted colorful decoration, and mica inserts allowed glimpses of the flames inside. A stan-







11.6 At Chicago's Columbian Exposition (1893) manufacturers eagerly displayed the stoves that were so popular in American homes. Open-grate stoves, such as the "Magic Ideal" (left), let the flames be seen. The "Cortland Howe Ventilator" (right) provided only flickering lights as seen through mica inserts, but received outside air through a floor grille. Both of these examples were crowned with decorative urns from which water evaporated. (*Report of the Committee on Awards of the World Columbian Commission,* 1901.)

11.7 This German design of a base-burner stove was said to hold a coal supply that lasted 10 or 12 hours. Air and flames moved horizontally through fuel, and ashes fell into the bottom of the stove. This model was meant to be installed in a wall, so that coal could be supplied and ashes removed in an adjacent room. (P. Planat, *Chauffage et Ventilation,* 1880.)

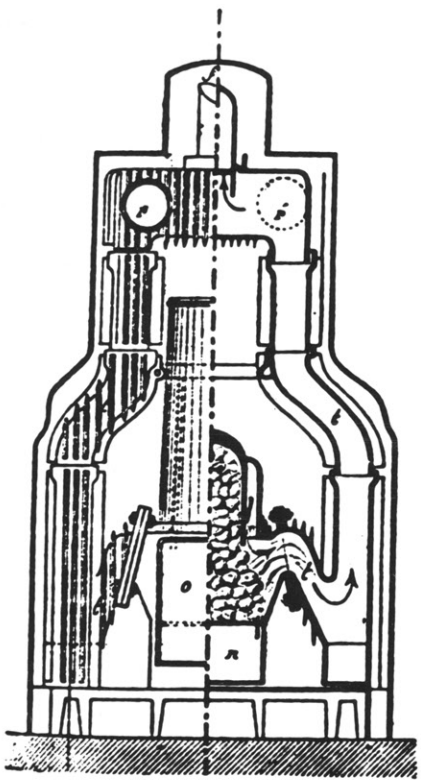
dard embellishment was an ornate metal vase at the top of the stove, large enough to hold a quantity of water that would add humidity to the hot dry air rising from the stove (fig. 11.6). In spite of the many technologically complex and heavily ornamented stoves that were available, the model most frequently seen was the globe stove, the "pot-bellied" stove of the American frontier. Dampers were the only significant technology of this simple design.

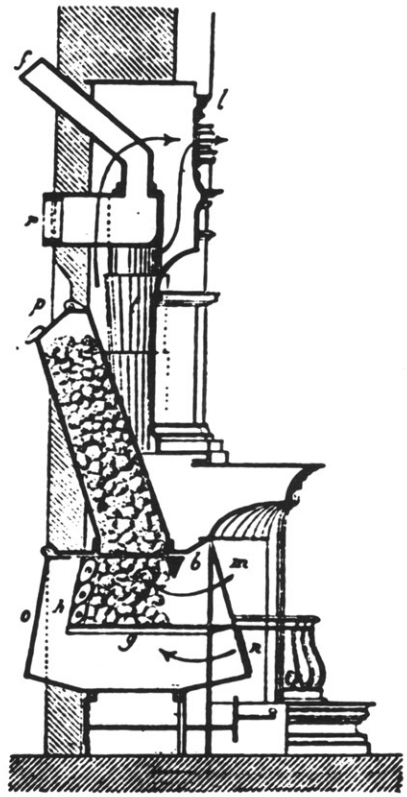
Base-burning stoves were designed to hold a sizable quantity of coal, with flames limited to a portion of the fuel supply (fig. 11.7). One of the best known of the base-burner stoves was patented in 1833 by Eliphalet Nott, the clergyman president of Union College in Schenectady, New York, who had previously designed a box stove for use in all the school's dormitory rooms. Coal was poured into a bin at the top of the Nott base-burner, and the fire burned in a receptacle beneath. A chamber over the flames received air from the room and released its heated air at the top of the stove. Coal was fed to the flames by a mechanically controlled aperture. In early models, as the stored coal became warmer, gas collected and might explode whenever the lid was raised to check on the fuel supply. A vent was added to allow that gas to escape to the flue, but if one forgot to close the vent the entire load of coal might burn.[15] The Nott stove never overcame this difficulty, but other models advanced the principle of the base-burner stove.

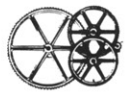
A problem of the westward extension of railways in the United States was the heating of railway cars. The English had seen no reason to heat

travelers: "Their idea is that it is quite sufficient to keep the feet warm and not exhaust the lungs or stupefy the brain. Passengers are provided with cylinders of hot water, renewed as occasion requires, on which to place their feet."[16] Much more was needed for rail travel in the United States, where it required days to cross the plains and winter weather was severe. The rocking motion of trains often caused rickety stovepipes to fall and even overturned stoves. Perhaps the most ingenious attempt to solve this problem was a stove holding a supply of water that was supposed to extinguish the fire when the stove fell.

By the 1870s, gas stoves had begun to appear, offering an escape from the bother of supplying coal or wood and removing ashes. Reflective metal surfaces were common in the gas fires that fitted into fireplace openings, and they could be shaped behind the flames so that heat was reflected into rooms at the same time that rising air was heated by the metal surface. Even more effective were shapes of ceramic materials over which gas jets played. Once heated to a glowing red incandescence, the ceramic units afforded a large radiating surface and bore a slight resemblance to the flickering light of a fireplace.







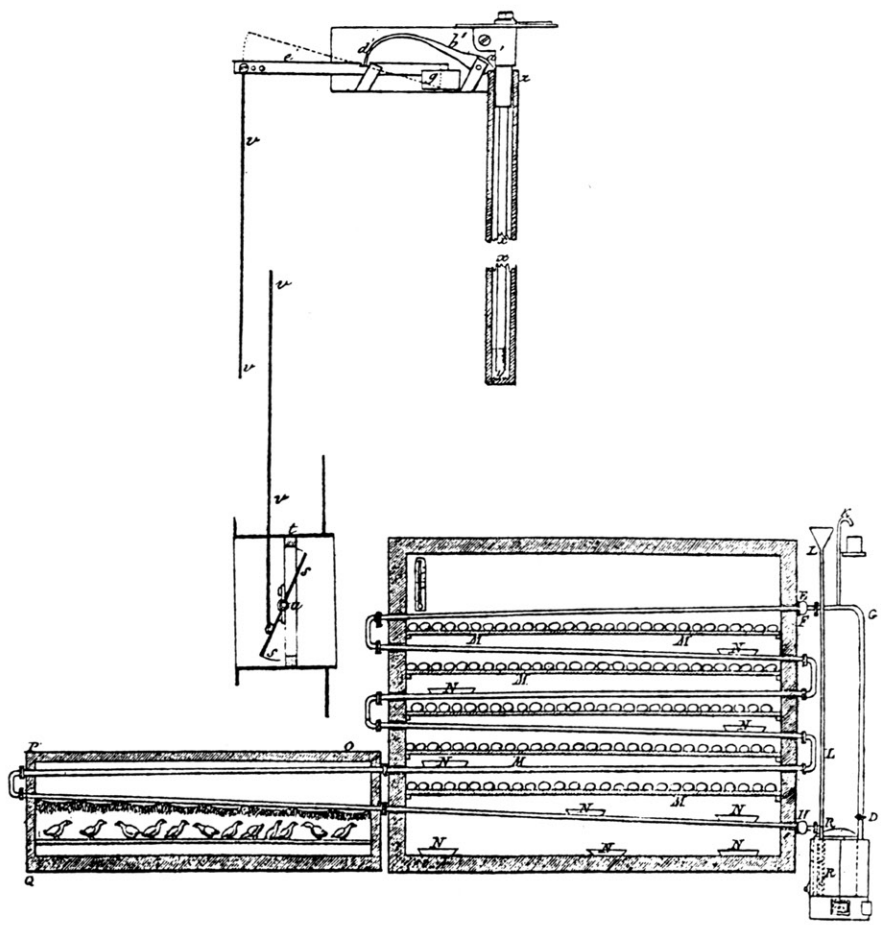
As industrial processes increasingly made use of steam power, there was nothing remarkable about piping some of that heat to points where it could be utilized for other purposes. Hot water was proposed in 1610 as a means of drying gunpowder, and by the late eighteenth century many greenhouses were warmed with hot water.[17] A diagram published in England in 1745 showed steam pipes looping through all the rooms of a three-story building and valves in each room to control the flow.[18]

A much more sophisticated device invented by Bonnemain, a Paris physician, was reported to the French Académie des Sciences in 1782. Intended for the incubation of poultry eggs, the system recirculated hot water (fig. 11.8). Apparently tests had shown that bubbles from boiling water could block the pipes, so an outlet at the uppermost point of the piping let steam escape, collecting condensate in a small container. Automatic regulation of the temperature was provided by a long rod that expanded, thereby closing off the flow of air to the fire.[19] In 1812 the Marquis de Chabannes published an English pamphlet on the Bonnemain system, adding his own variations (fig. 11.9). One of his diagrams shows steam circulating through a three-story building and includes an air outlet, provisions for recirculating hot water, and a pipe that allowed for expansion of the water in the system.[20] While French heaters based on Bonnemain's scheme usually made use of pipes of small dimension, Chabannes encountered difficulties that caused him to employ pipes 3 or 4 inches in diameter.[21] This meant that his heating system was seldom installed in buildings of formal character.

James Watt in 1784 extended a steam pipe from the boilers into his small office at the factory where the firm of Boulton and Watt manufactured steam engines. The pipe ran between two tin-coated iron plates, 3½ feet by 2½ feet, fastened an inch apart. Watt also placed similar heaters in two rooms of his house. He was not well pleased with the heat provided by these radiators, perhaps because the shiny tinned surfaces were less efficient than bare iron

11.8 Bonnemain's hot-water incubator was displayed in the 1770s. As water circulated among the racks of eggs, one loop of the pipe warmed the chicks. At the top of the incubator, a funnel permitted addition of water and a valve was available to release air from the pipes. An enlarged diagram (top) shows the mechanism by which the expansion and contraction of a long rod (x) within the boiler controlled the damper(s) that admitted air to the fuel. (*Gesundheits-Ingenieur*, 31 August 1907.)

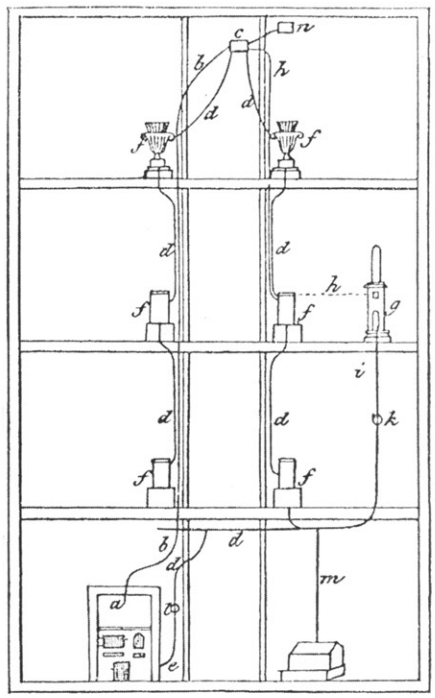
11.9 The hot-water heating system devised by the Marquis de Chabannes in the 1810s is said to have been installed in two London houses. Cold water (*c*, *n*) was fed from the roof to the furnace (*a*), and when heated, circulated to radiating vessels (*f*) in the rooms and to a bath (*m*). (*Gesundheits-Ingenieur*, 31 August 1907.)



plates would have been. In 1802 the firm of Boulton and Watt installed its first steam-heating system in a cotton mill. The design used hollow cast-iron columns to carry steam from floor to floor. Although there was an elementary logic to this system, heating by vertical pipes presented problems, whether columns or independent pipes were used. To evacuate air when heating was started and to keep the steam moving in the pipes, a valve was required at the top of each vertical, and condensation had to be drained at the bottom. In addition to the obvious danger of workers brushing against such columns, the building and piping connections were often damaged by expansion of the iron members at high temperatures. In one of Boulton and Watt's first projects, expansion was reported as "1/10 of an inch per 10 feet nearly."[22]

In the first mill installations using horizontal pipes, they were fed by a riser at one end of the building and ran along each ceiling to the other end of the building, where a valve allowed the escape of air, steam, and condensate. Later the ends of the heating pipes were connected to make a circulating system, and they were placed near the floor. It was necessary to slope horizontal pipes to prevent explosions when steam entered cool pipes and encountered water that had been trapped there.

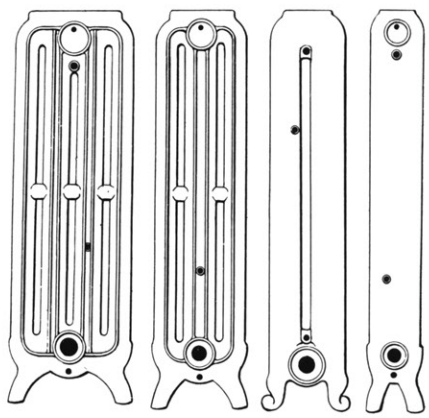
For years Jacob Perkins, who came to England from the United States in 1818 in order to promote his many inventions, experimented with the use of high pressure steam in engines and boilers. When his son Angier March Perkins joined him in 1827, these findings were applied to heating systems. Large pipes were required for heating systems in order to avoid cooling too rapidly and to assure that circulation was maintained. By providing a sealed system of pipes, water could



be heated above the normal temperature of boiling, and it would circulate through pipes of smaller diameter. In these systems the temperature of the water was usually between 220° F and 350° F and pipes were commonly one inch in diameter.[23]

The first installation of the Perkins system was for growing grapes in winter, but in 1832 the second heated the offices of a London insurance firm.[24] Angier March Perkins made improvements in the system during the next decade, and its use spread to the Continent and the United States. Jacob Perkins described his son's installation in the British Museum: "It would seem incredible, but it is a fact, that in this apparatus a stream of hot water which is not thicker than your little finger, carries the heat 700 feet, and then returns to the boiler at a temperature of 100 degrees."[25] The

Perkins system was occasionally used in residences and offices, but it and other steam systems were at that time more applicable to mill buildings and other industrial works, where exhaust steam could be utilized.



11.10 The manufacture of standardized radiator sections provided a great range of application. Any number of one-, two-, three-, or four-loop units could be combined to supply the required amount of radiation. Four-loop units were least efficient because the outer loops obstructed radiation from center loops. (*Engineering Magazine*, February 1898.)

11.11 The ease of casting metals and the flexibility of standardized radiator units encouraged production of an extraordinary variety of designs. Scrolls, frets, and other decorative additions abounded, and this dining room cabinet also warmed dishes and food brought from the kitchen. (Catalog of A. A. Griffing Iron Company, 1886.)

A handbook written in 1880 stated that "almost any respectable plumber can do hot water fittings, and they all know that one foot of four inch pipe warms 100 feet of air." This would mean that a room twenty feet long, fifteen feet wide, and ten feet high would require a large pipe running along most of two walls to make a total of thirty feet. For mills and greenhouses exposed pipes of such size might be acceptable, but they were not to be tolerated in Victorian parlors. When the heating system for Westminster Hospital was developed in 1830 by Joseph Bramah, the halls and stairways were warmed by radiators of a form somewhat more developed than those of James Watt. A series of closely spaced vertical pipes were supplied with hot water at the top and joined a return pipe at the bottom.[26] This arrangement was surrounded by a box, perforated at bottom and top to allow circulation of the air as it was heated. Radiators were most strongly developed in the United States, where extremes of temperature were far more challenging than those of the English climate (figs. 11.10, 11.11). In the late 1850s U.S. patents of radiators began to be filed, and about two decades later a radiator was introduced made by assembling a series of standard cast-iron units.

A heating engineer at the end of the nineteenth century compared U.S. practice with that of England. Because water in the British Isles often severely corroded wrought-iron pipes, cast-iron pipes of cumbersome dimensions were most often used.

> Within the last few years far more wrought iron pipe is being used for both the construction of wall coils, box coils, and mains; and in districts where the water is very bad, rain water is used in the heating apparatus.
>
> Wonderful strides toward improvement in installation of heating systems have been made in Great Britain within the last few years; the class of work is better, and far more radiators are used than ever before, although the average Britisher is still rather inclined to think them very ugly; but American radiator manufacturers are selling a large quantity of their goods, and are likewise manufacturing a class of goods to meet the requirements of the English market.[27]

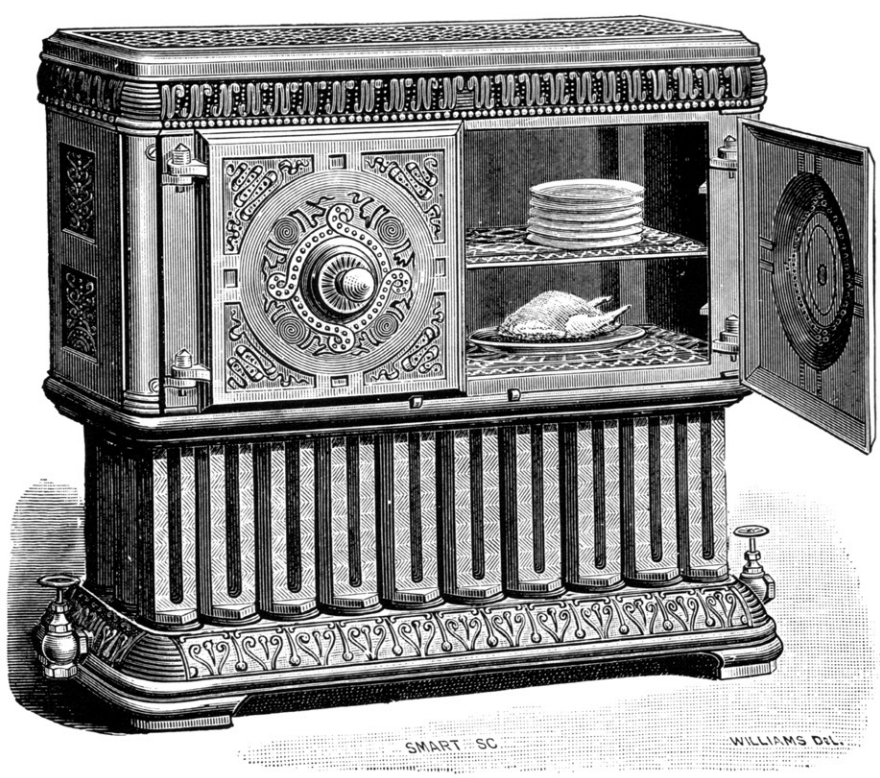
In the United States there was a tendency toward decorative effects in the castings that made up sectional radiators, but many architects still preferred to conceal them behind paneling.

Steam and hot-water heating required piping that could withstand the pressures that were present within the systems. Gun barrels had been manufactured in quantity during the long years of the Napoleonic Wars. For this purpose a strip of metal was heated a few inches at a time and hammered around an iron rod, the edges being lapped and welded together. As war ended, the use of piping for illuminating gas increased.

At first much of this need for small pipes was answered by screwing together gun barrels, either those that flaws made unsatisfactory for use in firearms or the unexpected surplus of factories. An English manufacturer, recognizing that gas pressure did not require a weld so strong as that for a gun barrel, in 1825 simplified the work by introducing the use of butt welds. The shape was obtained by pressing a strip of heated metal between two semicircular dies, in this way bringing its edges together. Another system, patented the same year, employed bell-shaped dies through which the metal was drawn, shaping and welding the tube as it advanced. Later the pressure of steam used in engines and heating demanded a return to the stronger lap-welded seams. To accomplish this, strips of metal with tapered edges were drawn through dies, reheated, and shaped by passing between rollers with concave faces that corresponded to the desired diameter of the pipe.[28]

The manufacture of pipes and fittings was begun in the United States by a Philadelphia firm in the early 1830s and by Joseph Nason and his partner James J. Walworth of Boston in 1847.[29] After working five years for the Boston Gas Light Company, Nason went to London, where he was employed for seven years by Angier March Perkins. Upon his return, Nason's newly organized firm purchased the stock of pipe and fittings of the unsuccessful New York branch of the major English maker of pipes.[30] In the first installations of hot water and steam heating, there were problems of preparing new systems, and the task of devising the connections and preparing the pipes required patience and ingenuity. Until the middle of the nineteenth century most pipe was imported from England. As domestic manufacture of pipe increased, imports were reduced, and no small part of production was the tubes and valves required for gas lighting.

Once it was possible to pipe steam under high pressure with satisfactory regulation of pressure, public building



11.12 In the 1910s the Illinois Maintenance Company coordinated the steam plants of buildings in Chicago's Loop district. Underground lines were installed across streets and alleys to connect the boiler plants that were kept active (black) with nearby buildings (hachure) in which the operation of boilers had been discontinued. (S. M. Bushnell and F. B. Orr, *District Heating*, 1915.)

complexes began to be connected by tunnels that contained pipes carrying steam from a central plant, a system that had long been employed for industrial buildings. District heating, the commercial distribution of steam from a central plant, began when Birdsill Holly, inveterate inventor and owner of the Holly Manufacturing Company, moved to Lockport, New York, in 1877. Within the year Holly had run pipes from the boiler in the basement of his house on Chestnut Street to a residence about 500 feet away. Soon 4 miles of piping had been laid to serve houses, stores, and offices in Lockport. As Holly's system grew, the American District Steam Company was established.[31]

The New York Steam Company began service in 1882 and nine years later it was serving buildings, including New York's city hall, along 5½ miles of mains and return pipes from its downtown plant and 2⅓ miles from its uptown plant.[32] These plants had been erected for the sole purpose of providing steam for distribution. The former manager of the company stated that the only buildings not gaining from a steam supply company were large buildings located in areas where there were no legal restrictions on having steam boilers. Among such buildings, he said, many did not have sufficient basement area to install an adequate system.

One of the early followers in the move toward district heating was the Philadelphia Electric Company, which in 1887 ran a steam line to an adjacent building. In generating electricity great quantities of steam were exhausted and wasted. Since at that time electric stations were usually located at the fringe of a city's business district, they were near office buildings large enough to be profitable users of that exhaust steam. Philadelphia's system grew slowly. A line was extended to the company's offices about a block away, but it was 19 years before the Jefferson Hospital contracted to buy steam and two department stores joined the system.[33] Competition in providing electric service was keen. At one time there were 20 electric companies and four district steam systems operating in Philadelphia. The sale of waste steam was a profitable activity for electric companies, for replacing boilers in the basements of large buildings usually meant also supplying the electric power that had been generated by the building's own steam engine.

This was the nature of district heating until the start of the century when the Illinois Maintenance Company introduced a different service to owners of Chicago buildings. The company undertook the operation of existing plants in downtown buildings, connecting them with underground steam lines in order to close down the smaller and less efficient plants (fig. 11.12).[34] Soon similar companies commenced operation in Boston and New York, the latter adding equipment to manufacture ice during the summers. Seasonal differences in the use of steam were not so great as one would suppose. Records of a large Chicago office building indicate that during a cold day of winter the amount of steam used to generate electricity during office hours was almost equal to that required for heating.

District heating systems were established in France, Germany, and other north European locales, but Great Britain apparently did not have an installation until around 1911.[35] Where circumstances offered an economical source of heat, district heating was not limited to densely built metropolitan locations. Reykjavik, Iceland, employs natural hot springs. In Virginia, Minnesota, a town of about

10,000 population with a climate similar to that of Moscow, the city system began in the nineteenth century with steam from a local sawmill and was augmented by steam from an electrical power company when that was established. Now the city has over 14 miles of mains operated by the city administration.

In addition to its legislative debates, the Houses of Parliament served for over 200 years as a battleground about the principles of heating and ventilation.[36] This single project illustrates the concerns and principles of heating and ventilation during that time, and it displays many features of technological endeavor when it is conducted in a public arena populated with strong-willed professionals and politicians. It all began in 1660, when Sir Christopher Wren attempted to relieve the heat from candles and MPs in the royal chapel, St. Stephen's, where the House of Commons had met for more than a century. In each corner of the room's ceiling, Wren cut a large square hole. In the room above he set over these openings decorative obelisks, around 7 feet high, through which the heated air could rise. Unfortunately, if the upper space were very cool a downdraft might reverse the intended movement of air. In 1723 this problem of ventilation was passed on to John Theophilus Desaguliers, a graduate of Oxford who lectured on science and presented frequent scientific papers before the Royal Society. His solution expanded on the work left by Wren. At each end of the upper room a small fireplace was built and connected to the two nearest obelisks by iron ducts near the floor. When fires were started

11.13 The Edinburgh laboratory and lecture room of David Reid so impressed audiences that a committee engaged him to plan the heating and ventilation of the Houses of Parliament. Fires in the principal demonstration table were fed by air entering from above, and smoke traveled through ducts under the floor to reach the chimneys. (D. B. Reid, *Brief Outline Illustration of the Alterations in the House of Commons*, 1837.)

in the fireplaces, their strong drafts drew air through the ducts and up from the House below. Although she was instructed to light the fires an hour before the House met, the action of this arrangement was defeated by the building's housekeeper, who resented the contraption's presence in rooms that were at the time assigned to her use. By waiting until a downdraft was well established, her lighting the fires added warm air from around the fireplaces to the mounting heat of the House. After Desaguliers invented a centrifugal fan for use in mines, one was installed above the chamber, and it was used there, turned by hand, for about 80 years. In 1791 the fan was moved to the center of the ceiling, and the chill of which MPs complained was corrected by installing a large stove beneath the floor of the House with warm air rising through a floor grating, 3 feet in diameter.

In the House of Lords there were complaints about cold and foul air. A solution was attempted in 1811 by Humphry Davy, the handsome and dynamic lecturer who had succeeded Rumford as leader of scientific studies at the Royal Institution. Davy provided fresh air through brick flues that were warmed by their running alongside chimneys. This fresh air entered the hall through a multitude of perforations in the floor. The peers' failure to compensate Davy for his efforts is recorded in a rhyme of the day:

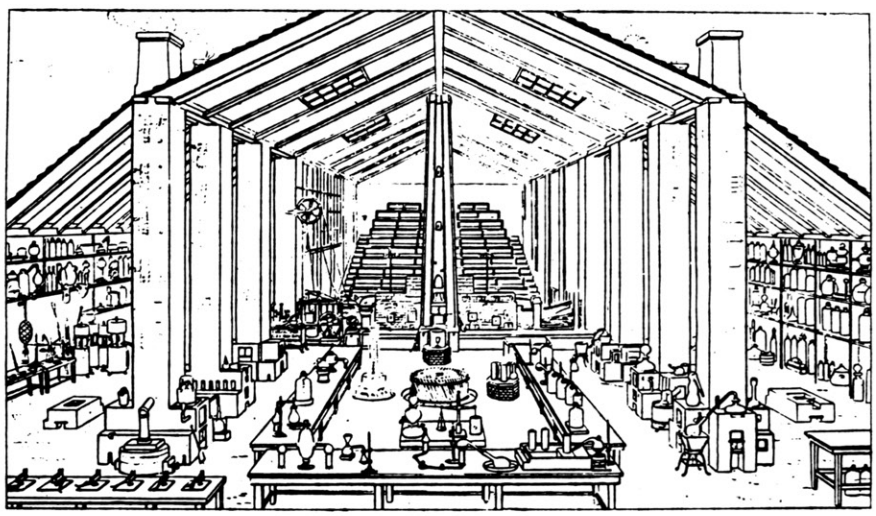
> For boring twenty thousand holes,
> The lords gave nothing—damn their souls.[37]

Conditions in the House of Commons were improved several years later by the Marquis de Chabannes, who had used steam pipes to improve the Covent Garden Theater. Steam pipes were set beneath the members' seats, and hot air was drawn off at the ceiling by ducts that had coils of steam pipes at their bases.[38] The logic of this system was impeccable, but it proved to be difficult to adjust and control. Chabannes had been promised payment only if successful and, because the costs were half again his estimate, the Commons consented to pay him only a small fraction of the cost.[39]

On 16 October 1834 careless workmen used stoves beneath the House of Lords to burn two cartloads of refuse from the Exchequer Offices; the Houses of Parliament burned. Soon plans to rebuild were underway, and an architectural competition for the new building was won by Charles Barry, an ardent classicist, with the assistance of A. W. N. Pugin, a medievalist of remarkably narrow enthusiasms. This odd partnership was ordained by the competition's requiring a Gothic air about the design.

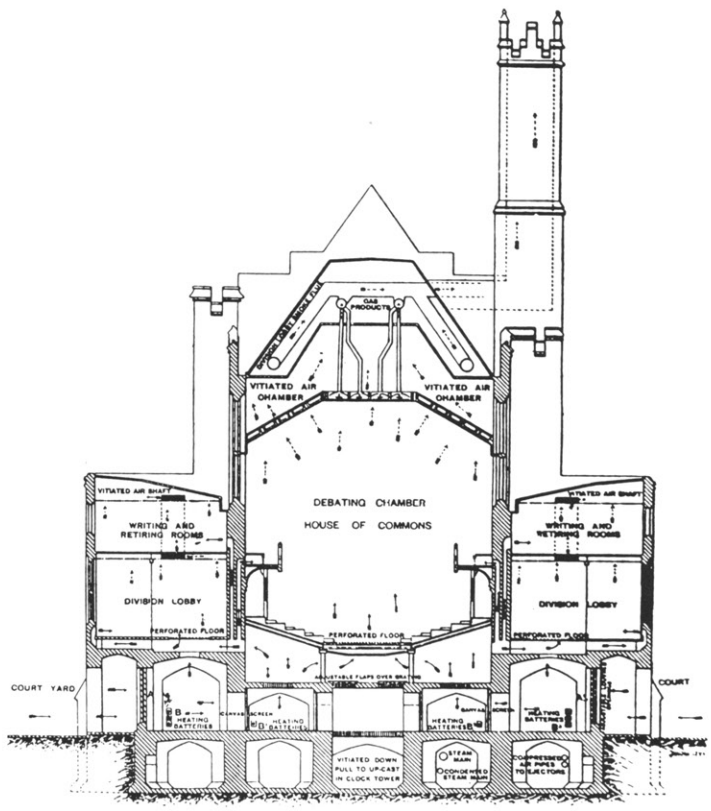
A few months before the fire, members of both houses had been among a group of visitors to the lecture room of David Boswell Reid during an Edinburgh meeting of the British Association for the Advancement of Science (fig. 11.13). When the University of Edinburgh failed to establish a chair of "practical chemistry," Reid had resigned his position there and set up his own program of lectures on chemistry and medicine. For purposes of demonstration, Reid's laboratory included a complex and efficient method of ventilation in which the downdrafts of various fires employed in experiments were led underground to flues elsewhere in the room. A year after the burning of the Houses of Parliament, a select committee concerned with plans for the heating and ventilation of the new building interviewed six experts on the subject, Reid among them. He

was put in charge of installing a system for the quarters of the House of Commons. It was agreed that his work was to be controlled by the architect only in those aspects related to the style or soundness of the building.



Reid's scheme started with air intakes in two towers about 300 feet above ground level. Even this precaution was sometimes insufficient. Several brickyards operated in the vicinity, and through the years discomfort in the Houses was caused by taking in, at different heights, scents from passing bargeloads of manure, a nearby factory that made strawberry jam, and the floating scum of "bluebilly," an extremely malodorous byproduct of the manufacture of illuminating gas. From the towers, air moved to a basement space in which it was filtered and warmed. As in Davy's scheme some 20 years earlier, air entered the chamber through perforations in the floor, which was covered by a coarse carpet through which the air could pass (fig. 11.14). From ceiling openings, much larger in total area than those previously provided, ducts drew the air to a tower that served as exhaust for most of the systems within the building. Reid spoke of the system as a "pneumatic machine," but the power of the fans then available to bring air in and the suction of heated exhaust flues were not sufficient to operate his "machine" effectively.[40]

Relations between Barry and Reid deteriorated, each deeply resenting the authority given the other. Reid was certainly irascible and vague regarding his plans, but Barry had in 1836 predicted a construction period of six years and was only laying foundations when that period elapsed. An excuse for delay would have been useful, and the diary of Barry's son in 1846 speaks of his father's "arranging his weapons of attack toward Dr. Reid."[41] In 1846 the architect was officially assigned the task of heating and ventilating the House of Lords, while Reid continued his work on the House of Commons. The system installed by Barry took heated fresh air to the ceiling, and it entered the room at the sides of the ceiling, being extracted at the center of the ceiling. The public arguments between Barry and Reid



11.14 Until the end of 1891, the House of Commons kept many of the basic characteristics of Reid's "upcast" system of ventilation. Treated air rose through the perforated floor and left through the ceiling, taking with it the heat of the 64 gas burners that lit the chamber. (*Industries*, 4 November 1892.)

and the long investigatory hearings conducted by committees of Parliament serve principally to identify the volatile temperament of Reid. Each of these professionals found his supporters, usually along party lines, as indicated by an epigram printed in the *Times* of London (2 July 1845):

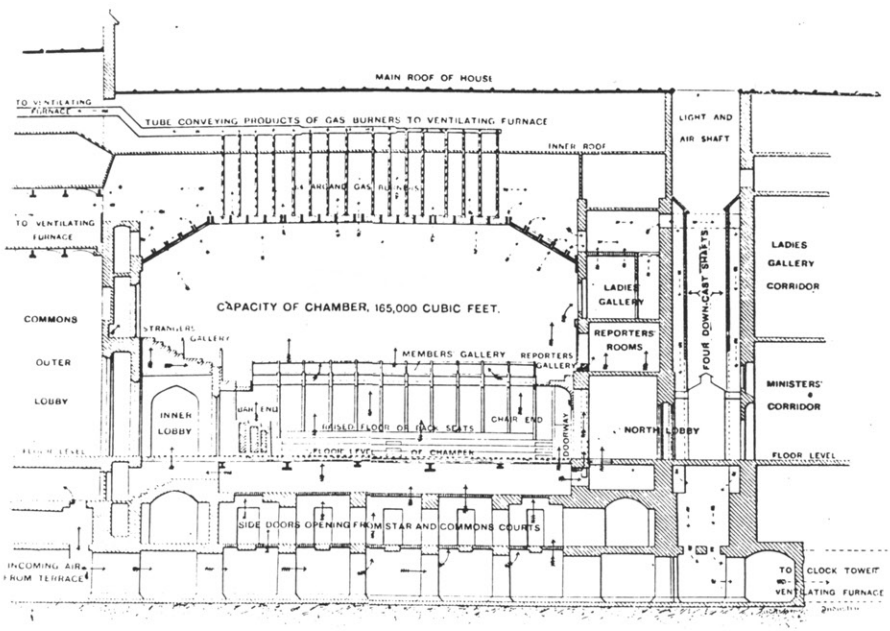
ON DR. REID'S BEING ALLOWED TO VENTILATE THE HOUSES OF PARLIAMENT BY ALTERNATE BLASTS OF HOT AND COLD AIR.

Peel's patronage of Dr. Reid
Is very natural indeed.
For no one need be told.
The worthy scientific man
Is acting on the Premier's plan
Of blowing hot and cold.

Faraday, who had been consulted by Barry, lectured at the Royal Institution in defense of the system used in the House of Lords, but there were still complaints about cold drafts down the peers' necks. Reid's lecture in reply was impressive, but his eloquence did not eliminate the dust that rose from his perforated floor. One angry MP proved this point by exhibiting a piece of gummy paper, grimy after having been fastened to a bench through an evening session.

By that time the architect and "ventilator" had fallen to accusing each other of being secretive and uncooperative. After dealing with an unmanageable tangle of supervision—committees, boards, and officials—Barry in the 1850s responded to questions about the date of completion and the cost by framing statements that were skillfully evasive. Benjamin Disraeli expressed one committee's frustration when he stated:

You hanged Admiral Byng, and the Navy increased in efficiency till we won Trafalgar. The disgrace of Whitelock was followed by the victory of Waterloo. We had decapitated Archbishop Laud and had thenceforward secured the responsibility of bishops. That principle we had never yet



applied to architects; and when a member of that profession was called to execute a very simple task and utterly failed after a large expenditure of public money, it really became the Government to consider the case, and they might rest assured that if once they contemplated the possibility of hanging an architect, they would put a stop to such blunders in the future.[42]

But Disraeli suggested no method of forcing a legislative body to proceed in an orderly manner.

In 1852 Reid was discharged, and three years later he emigrated to the United States where, after a stay at the University of Wisconsin, he became an inspector of military hospitals during the Civil War.

After Charles Barry's engineer had made a few changes in the Houses, Goldsworthy Gurney was given the task of correcting air movement in the House of Lords. Gurney believed that Reid's system, which principally relied on air being drawn through rooms by the force of an exhaust system, lacked sufficient power, and he preferred to push fresh air into rooms. To this end he reversed the system, after a series of studies in which the movements of air were traced by smoke, produced from burning over 60 pounds of gunpowder and other materials. The two towers that Reid had used as air intakes were converted to exhaust flues, and air was drawn from ground level. This system proved an abject failure, for in addition to occasional specific sources of odor, the Thames itself was at that period little more than an open sewer. Tons of lime were scattered on the water during the hours that Parliament sat, but there was little effective relief until the city's drainage system was improved. Dr. John Percy, who succeeded Gurney, believed that fans

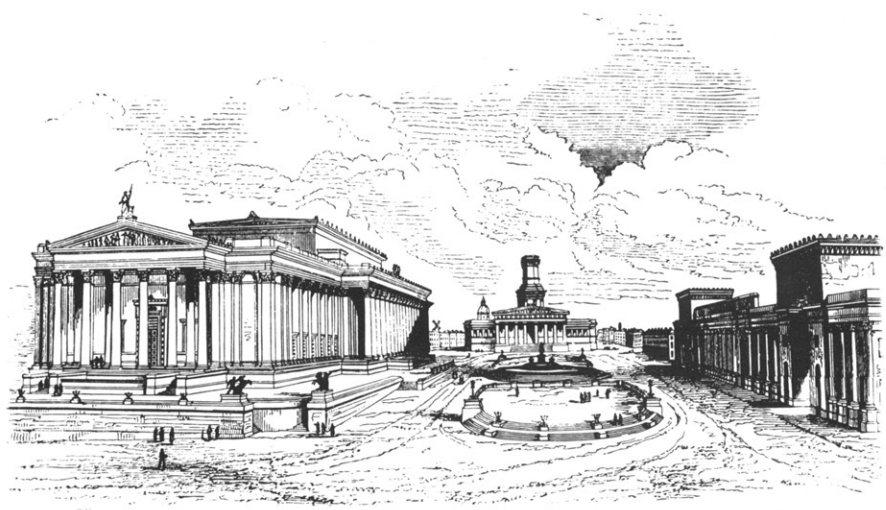
could never successfully challenge the air-moving force of heated chimneys. He maintained the ground level intakes installed by his predecessor and made the sensible recommendation that the courtyard from which air was taken should be kept free of horse dung. Percy's principal changes were the addition of intakes on the side of the building toward the river and the installation of sprays of water and steam that could humidify, cool, or heat the air as it entered the system. Percy's revision of Gurney's scheme survived into the twentieth century. A great deal of extemporaneous adjustment was apparently required: "When for any reason less heat is required, the radiators are simply covered with cloths."[43]

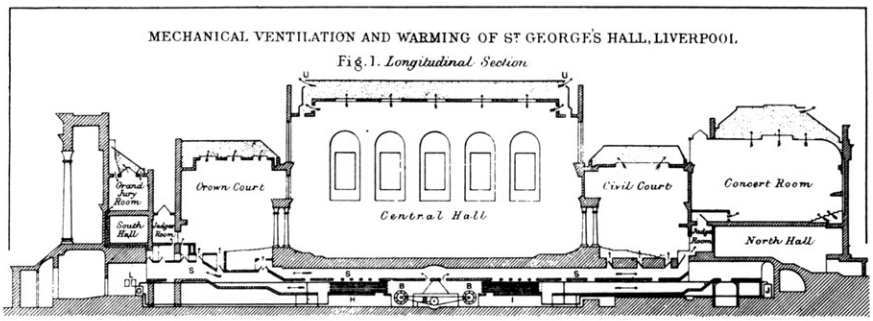
There were periodic appointments of committees to investigate the ventilation systems of both Houses and search for improvement. The most curious, a bacterial study of the House of Commons in 1903, showed that, although the organisms floating in the room proved not to be associated with specific diseases, they also had little political discrimination, being most prevalent at the seats of the government's ministers and least present at the benches of the same party's MPs.[44] The House of Commons was destroyed during World War II, and when restored a modern air conditioning system was provided.

If David Boswell Reid fared poorly in his work on the Houses of Parliament, his design of the heating and ventilating system for St. George's Hall, Liverpool, was more successful.[45] The project began some years after Reid had begun his troubled collaboration with Charles Barry and ended in 1854, shortly before Reid emigrated to the United States. St. George's Hall was an imaginative agglomeration of Classicism by architect Harvey Lonsdale Elmes, and it solved the difficult problem of combining a large hall, two court rooms, a concert hall, and a smaller lecture room (figs. 11.15, 11.16). Collaboration began early, and the fact that Reid's system was viewed favorably over 50 years later indicates the cooperation of architect and engineer on the requirements of the design. The ventilation system was essentially what Reid had attempted in the House of Commons. Air entered at the bottom of rooms and was exhausted through the ceiling, taking with it the heat and odors of gas lighting.

11.15 In the original plans, St. George's Hall, Liverpool (left), was to exhaust air through a large ventilating tunnel leading to the tower of a Daily Courts building (background). When plans for the Daily Courts were abandoned, the ventilation scheme for St. George's Hall, which was already under construction, was changed to employ fans and vertical air shafts that would not be tall enough to harm the building's classical silhouette. (D. B. Reid, *Illustration of the Theory and Practice of Ventilation,* 1844.)

11.16 To ventilate St. George's Hall, Liverpool, four fans, each 10 feet in diameter, drew outside air into a basement passage, where it was heated by both steam coils and hot-water coils. All rooms, except the Central Hall, were exhausted through four shafts that extended to the uppermost parapet level. (*Civil Engineer and Architect's Journal,* 1 May 1864.)

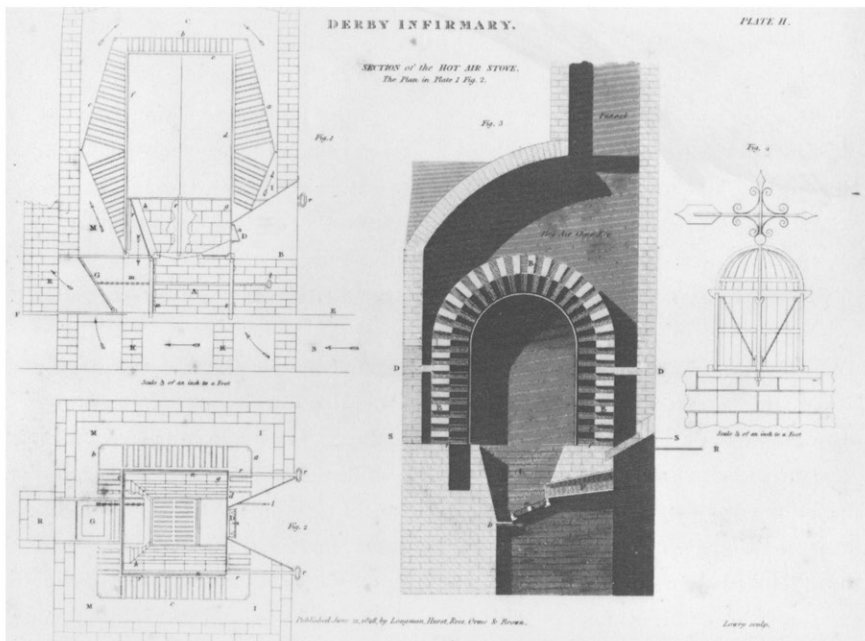




Fresh air was drawn into St. George's Hall down two large shafts. Once it had reached the basement levels, the air was heated by warm-water coils and supplementary steam coils or it was cooled by running water from city mains through the coils. Moisture could be added to the air by sprays of steam, and the shafts that admitted fresh air held water sprays that cleared particles from the air. Between the ceilings of rooms and the roof, horizontal flues separately gathered the exhaust air from major rooms and the smoke from the fireplaces that were used to ventilate small offices and meeting rooms in the building. The dictates of classical architecture did not permit towers so tall as those allowed by the somewhat medieval style of the Houses of Parliament, so the four vertical shafts that expelled smoke and foul air from St. George's Hall were fitted with metal louvers to prevent downdrafts. The ceiling of the central hall, 169 feet long by 74 feet wide, was so near the top of the towers that they could not effectively serve to evacuate air from that space. Louvers at the ends of the central hall's attic permitted air to be exhausted, the north or south louvers being opened according to the direction of the wind.

Thermometers were scattered about the system and read regularly. Strands of thread and small paper cylinders were hung at intake and delivery registers to provide evidence of the system's activity. Although St. George's Hall lacked most of the automatic controls that were later developed, only minor adjustments were made through the first half-century the building was used. This was the largest and most complete installation designed by David Boswell Reid, in contrast to the political muddle of the House of Commons. When St. George's Hall was completed, its system of heating and ventilation was overblown and excessively complicated; however, the size and complexity of the building made the scheme a remarkable exhibition of the scientific and practical knowledge of that time. In fact, during construction the building committee had found it necessary to dampen Reid's enthusiasm by reminding him that "the building was not intended as a mere shell in which to exhibit the principles of perfect ventilation."[46]

The eighteenth century has sometimes been called the Age of the Greenhouse, because it became fashionable for the wealthy in northern Europe to indulge themselves with the luxury of out-of-season fruits and flowers. Many greenhouses were heated by flues running along a back wall or through the floor as they made their way from a stove to a chimney. Not only was it difficult to maintain a draft for a horizontal distance long enough to be gen-



11.17 Devised by William Strutt and developed by Charles Sylvester, the cockle furnace was installed in 1806 in the Derby Infirmary. Around the iron jacket of the cockle a perforated shell of brick heated fresh air that rose from an underground passage. (C. Sylvester, *The Philosophy of Domestic Economy*, 1819.)

11.18 In planning Pentonville Prison (London, 1841–1842), Colonel Joshua Jebb, Surveyor-General of Prisons, saw a close connection between construction of a prison and the discipline under which it might operate. Although he insisted that there be no possibility of sound traveling between cells, he also insisted on healthful conditions. It was reported that each of the cells received between two and three air changes per hour. (J. Jebb, *Report on Pentonville Prison*, 1844.)

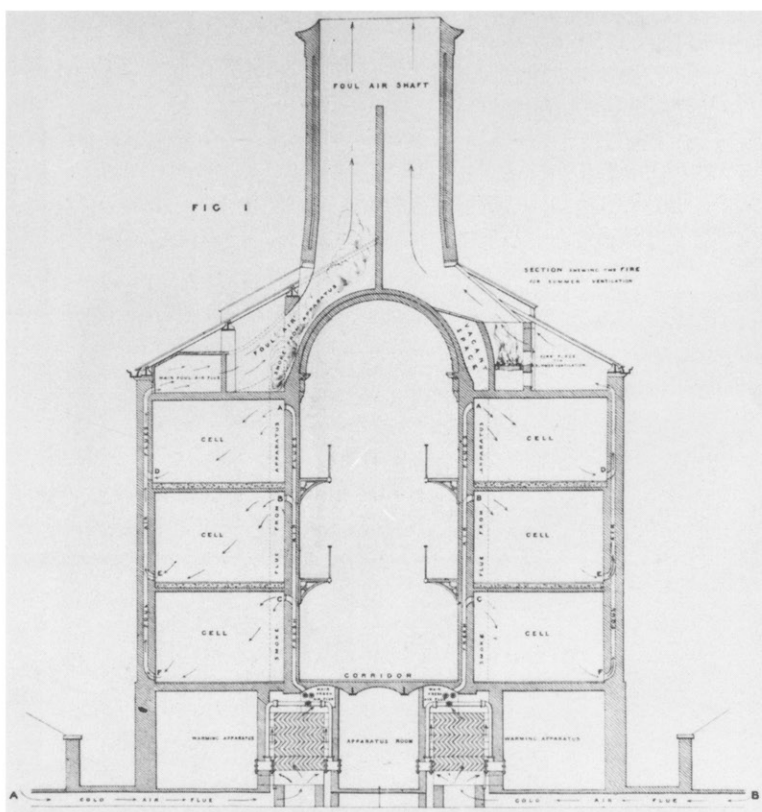
uinely useful in heating a greenhouse, but any leak in a flue might release coal gas that could rapidly damage the plants. A method of flue heating for buildings was found in what was called the "English smoke pipe system." Its flue and heating surface was a cast-iron pipe, extending upward through floors of a building and entering the chimney at the attic level. Although the danger of fire was inherent in the smoke pipe system, it seems to have been briefly popular around the 1820s, even being used with horizontal runs on the different floors of a textile factory.

A safer and more reliable method of heating provided two separated air flows, one to feed the flames and carry away smoke, the other to heat air and distribute it to the rooms of a building. (This problem is little more than a large-scale restatement of the various early systems in which iron fireboxes were set in fireplaces.) The simplest method of doing this was to locate a stove in a small chamber from which warm air could rise into the room above, where it was desired. The thirteenth-century city hall in the German city of Lüneburg had three stoves in a basement room below its principal meeting hall. Fresh air entered the basement and heated air rose under the councilmen's seats, where iron lids permitted each of the officials to regulate his own comfort.[47] In one German castle, heat from a tile stove rose through a perforated floor. None of these early warm-air heating systems did much more than relegate the stove and the bother of caring for fires to a space adjacent to the room that was to be heated and, in many cases, provide for the stove to be tended by servants without bothering their masters.

English textile mills in much of the eighteenth century were heated by open fires placed about each floor of

the building. Profiting from trials made by others, William Strutt in 1792 developed a safer heating system for Belper Mills. Many mills had changed to the use of cockles, a form of closed stove, but cockles often overheated, which was dangerous in the highly flammable environment of a mill.[48] In Strutt's design for the Belper Mills, the cockle stove was surrounded by a brick enclosure into which fresh air was admitted (fig. 11.17). Another brick shell, arching only a short distance from the iron surface of the cockle, had a pattern of perforations in its brickwork. This jacket increased the heating surface and so assured a higher temperature in the air that rose to the upper floors of the factory. By 1806, when Strutt planned the heating system for the Derby Infirmary, his design had been refined. Here the brick covering of the cockle had greater mass, and less than an inch of space was left between the iron and brick surfaces. Fresh air was admitted through a slit surrounding the bottom of the brick shell. The air was drawn inward to the surface of the cockle through openings in the brick, moved upward along the iron surface, and once more passed through openings in the brickwork to reach the ducts that carried air to the rooms. Strutt's respected position among mill owners and his many scientific acquaintances assured that his ideas were applied in many buildings executed by others. Strutt's warm-air heating system was further developed by his friend Charles Sylvester, who had been tutor of Strutt's son. In his book *The Philosophy of Domestic Economy*, Sylvester explained the Strutt system. As a consultant on building projects he developed applications, and as a manufacturer of stoves he made the system available generally. By 1817 Sylvester had found it difficult to make certain that the brick shell was built correctly around the cockle without providing close personal supervision of the work. As a substitute for such intricate brickwork, he devised an iron jacket perforated by tubes that led to points near the surface of the cockle. Little supervision was required when workmen assembled the simple parts that came from the factory.

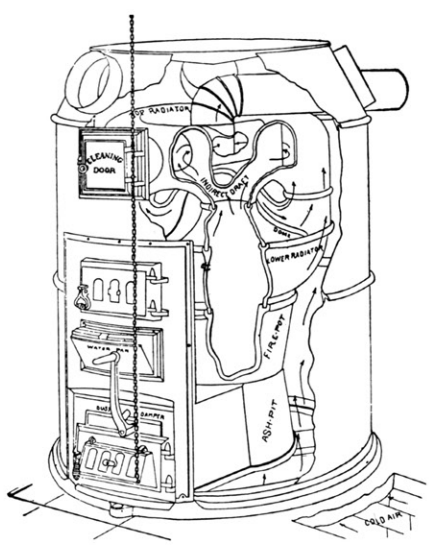
One of the first systems to confront the problem of providing warm air to a large number of rooms from a single source was that of the model prison at Pentonville, built in the 1840s under the supervision of Joshua Jebb, England's Surveyor-General of Prisons.[49] Fresh air was heated in a basement furnace room and left there through a passage built beneath the ground-level corridors (fig. 11.18). Individual ducts rose within the walls to release air above the door of each cell in the three stories of the building. In the outer wall of each cell an opening near

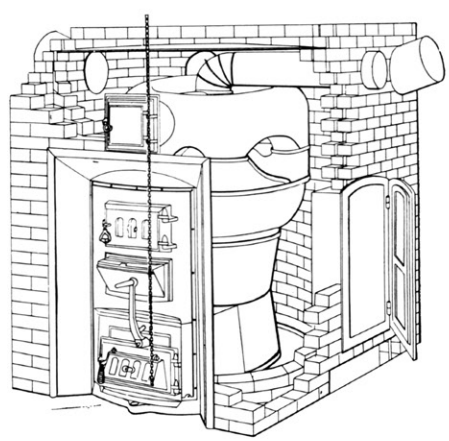


the floor let air escape into a vertical channel that led to a large horizontal duct in the attic, which in turn emptied into a vertical shaft that extended 20 to 25 feet above the roof.[50] In winter the flue from the furnace rose inside this exhaust shaft and guaranteed a strong draft; in the summer a fire was maintained for that purpose. This system was long an example to be followed in the construction of new prisons, and one visitor is said to have thought its air as fresh and invigorating as that in the Crystal Palace.[51]

At the end of the nineteenth century, warm-air heating was generally limited to residences or to buildings not much larger than residences and to assembly places where the crowds caused ventilation and cooling to be a major concern. For the smaller buildings, warm-air heating was little more than that provided for the burghers of Lüneburg five centuries before. In a basement the cast-iron furnace was surrounded by brick walls or a sheet-metal jacket (fig. 11.19). Furnace gases went directly to a chimney and fresh or recirculating air passed between the furnace and its surround before rising through chases or sheet-metal ducts to the rooms above. In some designs the surfaces of the furnace were shaped in ribs or corrugations to increase the amount of surface radiating heat. As the air cooled in rooms it usually returned to the basement through grilles or down a central stairwell (fig. 11.20). In larger installations air was drawn through racks of pipes containing steam or hot water and distributed in a similar manner.

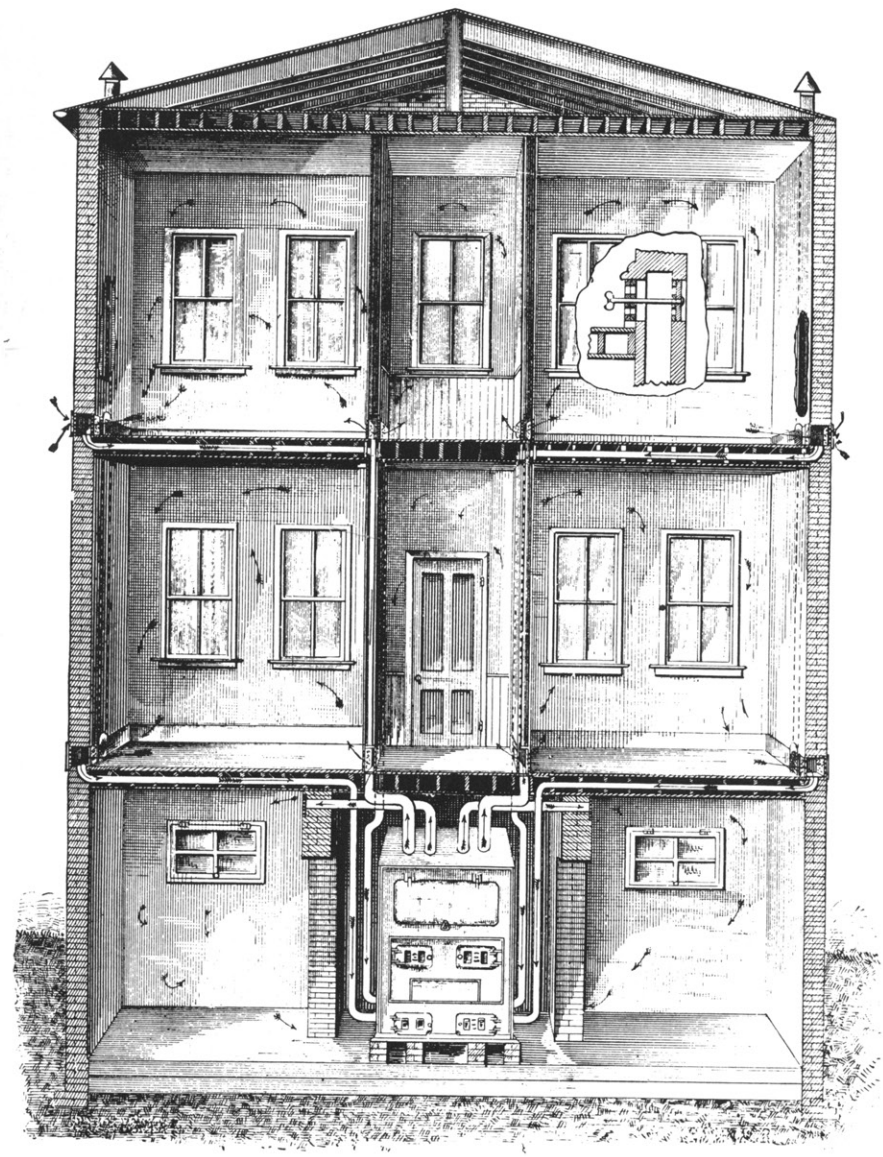
Steam heating was more popular for large buildings, particularly if their purpose required division into small spaces. Steam radiators placed under each window and provided with individual controls allowed for any replanning of the building that might be executed in the future. As a writer reported in the *North American Review* in the 1880s: "Even for ordinary dwellings, [steam heating] is being gradually extended; while for larger blocks, such as apartment houses, hotels, manufacturing establishments, school-houses, and other large structures, the system is so greatly in demand as to have given rise to new and extensive industries devoted to the manufacture and installment of the necessary apparatus."[52] A system of radiant heating by coils of hot-water pipes distributed in concrete floor slabs and plastered walls was used in the United States during the 1940s and 1950s. It provided well-distributed heat, but was slow to respond to sudden needs.





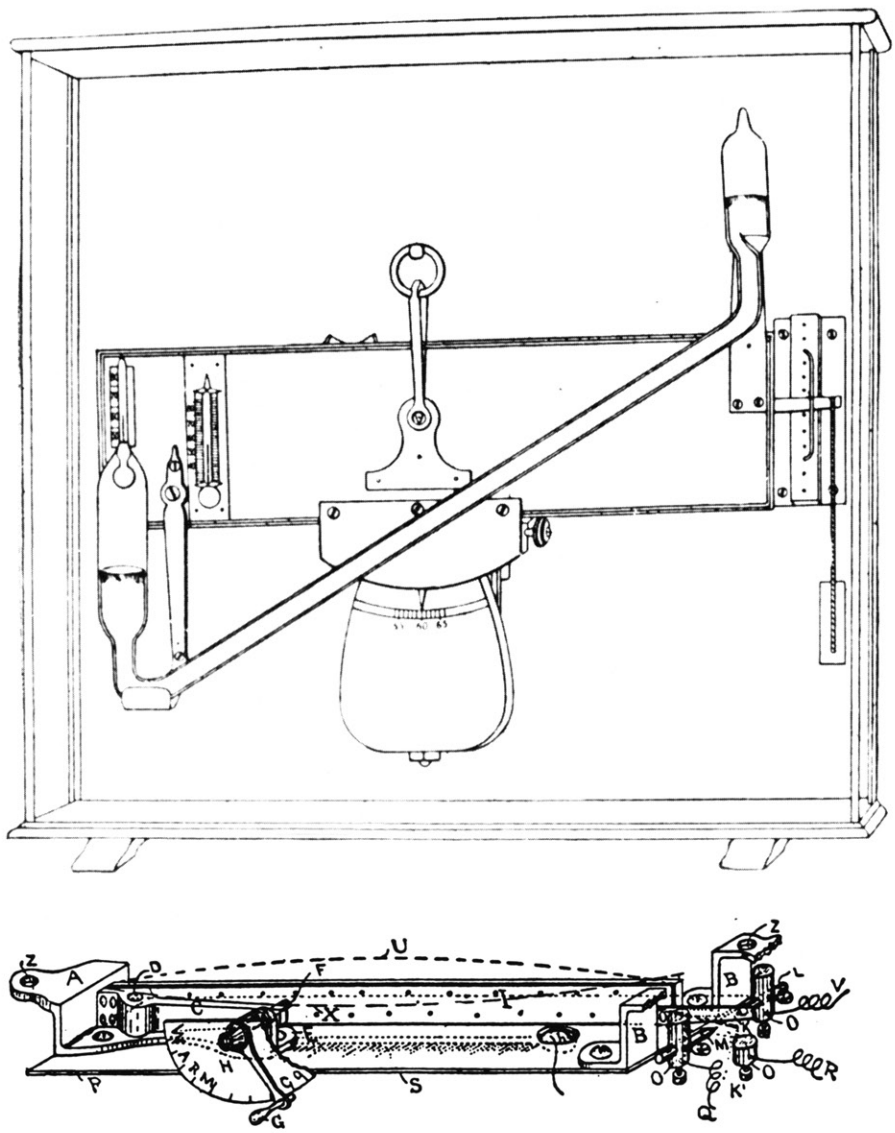
11.19 Residential hot-air heating systems at the start of the twentieth century commonly had round furnaces, little more than cast-iron stoves, as their central element. The surrounds were of two sorts: a "portable setting" (left) that consisted of a casing made of one or two layers of sheet metal, or a "brick setting" (right) that was a small chamber with masonry walls. (*Engineering Magazine*, June 1898.)

11.20 This diagram illustrates a residential heating system of the 1880s in which ducts were provided for both the supply of warm air and its return to the furnace. The advertiser pointed out that "in a majority of the houses already built, boxes in their basements can be constructed." An inset at the top shows a register that can be adjusted to either return air to the furnace or admit outside air. (*Useful Information Pertaining to the True Systems of Heating and Ventilation of Buildings*, 1885.)



Steam heating and hot-water heating were subject to all the long-standing complaints about stoves and the parched air they produced. Even when radiators were concealed in the most elaborate paneling and grillwork, it was common to find atop them a shallow pan of water that was intended to increase humidity. Steam and hot water were the most efficient methods of moving heat for long distances, for when hot-air ducts became too long their efficiency diminished and the difficulty of equalizing the flow of air increased. In addition, the acceptance of air conditioning required delivery by air, because of the condensation that would form on radiators filled with chilled water. Warm-air systems afforded the best opportunity to provide ventilation, control humidity, and in the summer utilize the same installation for cooling.

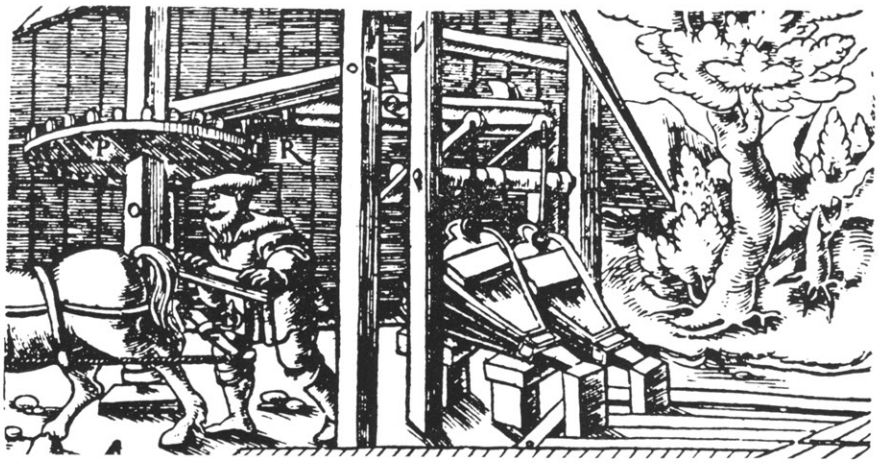
The automatic regulation of heating systems developed as a result of the discovery that materials expand or



11.21 Thermostatic controls were available by the 1890s, although often rather complex in nature. Above: Mercury was poured into a balanced glass tube until bulbs at the ends were half-filled; the lower bulb held ether over the mercury. Cold caused the ether to contract rapidly, drawing more mercury into its bulb; the tube then tilted and thus activated the furnace controls. Desired temperatures could be set by adjusting the fulcrum on which the tube balanced. Below: A bar was fabricated by riveting together strips of brass and hard rubber. Because of the two materials' unequal expansion, the bar would bend with temperature changes, making electrical contact with the heating controls. (J. S. Billings, *Ventilation and Heating*, 1893.)

contract when their temperatures rise or fall. This knowledge was utilized in John Harrison's development of compensators that would adjust his marine clock for changes of temperature. His first device, made in 1726, relied on the lengthening of metal rods, the principle used some 50 years later to regulate the fire in Bonnemain's incubator. Harrison's second device was based on a bimetallic strip, two metals with very different coefficients of expansion bonded together so that heat would cause the strip to bend to one side. Whether they involved the use of floats on expanding liquid, the expansion of rods, or bimetallic strips, such devices converted the thermal expansion of materials into mechanical movements that regulated valves or dampers to control the flow of air to the fire or the flow of heated air or water from the furnace. Nevertheless, during sessions of Parliament at the end of the nineteenth century, attendants trudged about the Houses carrying thermometers and inspecting others that were fastened on the walls.

The need to control heat or refrigeration in industrial processes spurred the development of thermostats whose principles were often applicable to the heating systems of buildings. In addition to the principles employed in previous thermostats, in the 1910s devices were introduced that



depended on the expansion of certain fluids in metal bellows, thin-walled containers that were corrugated around their circumferences.[53] The regulation of furnaces by thermostats located in rooms of buildings was made possible by electrical connections of later types (fig. 11.21).

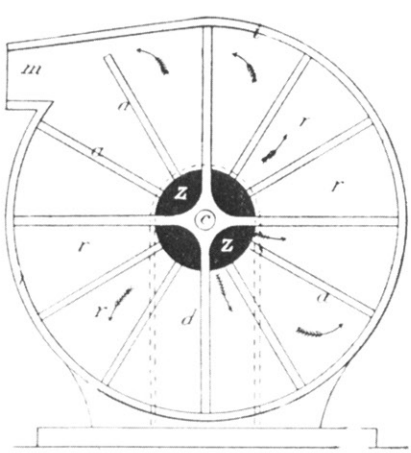
The required capacity of heating systems could be determined with reasonable accuracy after the publication of handbooks, such as that of Thomas Box (1876), which included formulas for heat loss in buildings and factors for estimating the transmission of heat through walls of masonry and other materials.[54]

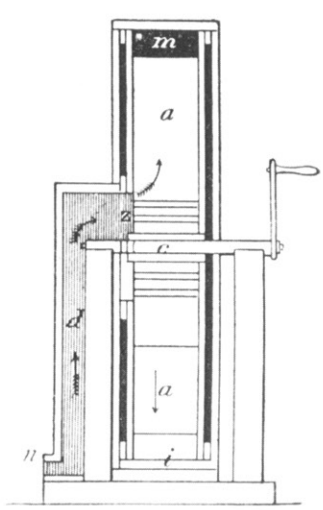
Any regulation of heating systems required an effective method by which air could be supplied to and removed from the spaces that were to be heated. In *De re metallica*, the sixteenth-century German metallurgist Agricola had referred to the use of fans and other mechanical means of drawing air and gases from mine shafts (fig. 11.22). Nevertheless, such machines were seldom used until the start of the nineteenth century when air pumps with strokes as long as 8 feet were introduced.[55] It was the 1830s before fans were commonly used in mining.

When Desaguliers was busy finding a way to ventilate the House of Commons, he introduced a fan in which air was admitted at the hub of a paddle wheel 7 feet in diameter and was driven out in a tangential direction (fig. 11.23). As they were turned by hand, the 12 blades of the fan forced air out of the fan's jacket. The Admiralty requested a demonstration of Desaguliers's machine, but the Sur-

11.22 The earliest methods of forced ventilation were often designed for the protection of miners. This system of horse-powered bellows was shown in a 1555 edition of Agricola's *De re metallica*. (*Refrigerating Engineering*, March 1934.)

11.23 After devising a machine to draw foul air from the mines operated by the Earl of Westmoreland, Desaguliers developed this "fanner" in 1734 for use in hospitals and prisons. The wheel was 7 feet in diameter and 1 foot wide. Air entered near the axle, and cranking by hand forced air through the outlet. (W. Bernan, *On the History and Art of Warming and Ventilating Rooms and Buildings*, 1845.)





veyor of the Navy insisted that sailors first demonstrate the efficacy of "wind sails," a traditional method of forcing air below decks, and he left before witnessing the performance of Desaguliers's invention.[56] Few significant advances in the construction of fans were made in the century that followed the work of Desaguliers. The major improvement was to change the casing of the fan from circular to spiral, gradually enlarging the space between the blades and casing as air neared the outlet. Curved blades were experimented with, and formulas were developed for the relationship of fan size and the amount of air that could be moved. In the 1880s builders of an English tunnel made use of a fan 18 feet in diameter.[57]

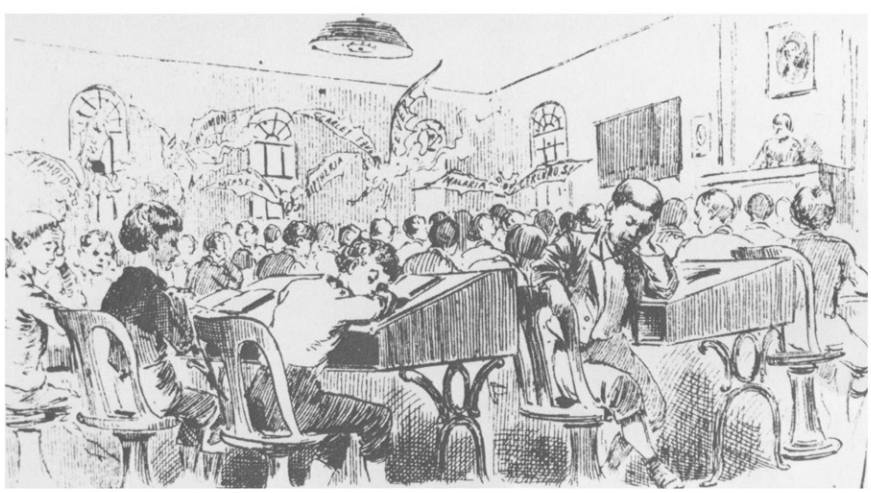
By the 1870s, fans, which had been seldom used outside factories, began to be installed in schools and auditoriums. Electric motors contributed much to expanding the use of fans, but the heated chimney remained a common method for moving air. When members of the American Society of Mechanical Engineers, meeting in 1897, discussed the relative efficiency of heated chimneys and fans for exhausting air, a speaker presented data that proved a fan to be at least three times as efficient as a chimney; but one listener insisted that fans were "poor devices" and that chimneys were almost 14 times as efficient.[58]

For many years *Principles of Warming and Ventilating Public Buildings*, published in 1824, was the English-language handbook for problems of ventilation, and its stipulations were frequently borrowed by other writers on the subject. The book's author, Thomas Tredgold, had studied under an architect before setting up as an engineer and a prolific writer of books on the practical aspects of building construction. According to one of the rules he presented, every person in a room should be provided with 4 cubic feet of fresh air every minute. Others thought Tredgold's recommendations for ventilation excessive. Arnott, who favored supplying 2–3 cubic feet per person per minute, claimed: "There are, in England, many persons who, under all circumstances, call out for open fires and open windows, and by the cold currents and other concomitants of a ventilation more than necessary, prodigiously waste fuel and injure or kill their children and friends by catarrh, rheumatism, etc."[59] A few decades later, a dissent from the United States was to be found in *The American Woman's Home*, by Catherine E. Beecher and Harriet Beecher Stowe: "The great majority of the American people, owing to sheer ignorance, are, for want of pure air, being poisoned and starved; the results being weakened constitutions, frequent disease, and shortened life."[60] In spite of the fervor of this statement, it was accompanied by the requirement of one hogshead of fresh air per person per hour—only about 8½ cubic feet. Much of the debate on ventilation and temperature requirements appears to have related to personal and, even more, national perspectives. Around 1840 an Irishman in the United States wrote: "Casual visitors are nearly suffocated, and constant occupiers killed. An enormous furnace in the cellar sends up, day and night, streams of hot air. . . . It meets you the moment the street-door is opened to let you in, rushes after you when you emerge again, half-stewed and parboiled.[61]

In the 1770s Antoine Laurent Lavoisier, the founder of modern chemistry, disproved the phlogiston theory and showed that air consisted of two gases, one combustible and the other not. His experiments in combustion and oxidation were extended to include the behavior of animals in

air, oxygen, and nitrogen. It was Lavoisier's conclusion that harmful atmospheres resulted from the increase of carbon dioxide, and that this inhibited the body's absorption of oxygen. Thus the problem of ventilation was not the depletion of oxygen in a room but the increase of carbon dioxide. The theory was incorrect, but it persisted for a century. A later experiment showed that an animal could recover from 45 minutes in an atmosphere that was 30 percent carbon dioxide. At the same time, it was found that the increased amount of carbon dioxide that occurred in crowded rooms was insignificant. Max Joseph von Pettenkofer, a professor of medicine at the University of Munich, in 1863 found that an atmosphere having 1 percent carbon dioxide could be breathed for long periods without ill effects. (Normally, air contains about 0.03 percent carbon dioxide, and one expert in 1928 said that "the worst ventilated room" reached only 0.5 percent carbon dioxide.)[62] This meant that even the worst conditions of crowded rooms could not be harmful, at least not because of the presence of carbon dioxide.[63] However, Pettenkofer, who did not subscribe to the germ theory of disease, was convinced that the amount of injurious organic impurities breathed into the air were indicated by the amount of carbon dioxide present. This relationship encouraged the continuation of the popular belief that the gas itself was harmful.

A remarkable connection was made in the middle of the nineteenth century when the theory of poisonous "organic effluvia" led to a scientific association of gaseous characteristics with specific ailments (fig. 11.24). One writer stated this chemical extension of the miasmic theory of disease thus: "On the whole, it would appear that sulpheret of ammonia is the morbific agent exciting typhus fever, sulpheretted hydrogen being the pestilential virus [meaning "causative agent"] producing yellow fever and the bilious remittents and agues of tropical climates."[64] Another scientist was cited as having proved the relationship between hydrogen and malaria. It must be remembered that at this time Pasteur was engrossed in the studies that would soon result in germs being identified as the cause of disease. Until Pasteur's findings had been generally accepted around the end of the century, it was commonly assumed that diseases were spread by vapors from infected or putrid materials. In that context it is not surprising that any discussion of ventilation might consider a specific relationship between different gases and illnesses.



11.24 With the advance of public education, schools became a prime interest of those concerned about ventilation standards. Here ghostly flying monsters, bearing the names of specific diseases, flit over the heads of drowsy students. (Bettmann Archive.)

The notion of organic poisons was advanced by the experiments of Charles Brown-Sequard and Jacques d'Arsonval in 1887. In one study, air entered the first of four boxes containing healthy rabbits, and air from that box supplied the next, and so on until the last box was provided only with air that had passed through all three others. It was reported that the fourth rabbit died first, the third died next, and the first two survived. When the air entering the fourth box was passed through sulphuric acid, the fourth rabbit survived, but the third died.[65] Findings of this sort greatly strengthened the belief in there being organic poisons exhaled into the air. As late as 1911 an experimental group reported animals made ill by injections of material from the breath of other animals, but subsequent experiments did not corroborate those results.

Carbon dioxide was branded the culprit, either as a poisonous gas or a vehicle of injurious substances, until the 1880s when a Dutch experimenter theorized that the effects of poorly ventilated rooms were more a matter of physics than of chemistry, that they resulted from excessive levels of temperature and humidity in the air. As scientists at the University of Pennsylvania wrote in 1895:

> The discomfort produced by crowded, ill-ventilated rooms in persons not accustomed to them is not due to the excess of carbonic acid [carbon dioxide], nor to bacteria, nor, in most cases to dusts of any kind. The two great causes of such discomfort, though not the only ones, are excessive temperatures and unpleasant odors. Such rooms as those referred to are generally overheated, the bodies of the occupants, and, at night, the usual means of illumination contributing to this result.[66]

This view was supported by extensive studies made in Germany controlling airflow, temperature, and humidity for human subjects closed in cabinets of little more than 100 cubic feet.

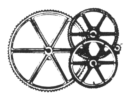
Through the nineteenth century there had been a constant increase in the amount of fresh air recommended. After Tredgold's figure of 4 cubic feet per minute per person came David Boswell Reid's 10 cubic feet (1835); by 1857 the English Barracks and Hospital Improvement Commission raised the figure to 20 cubic feet. By this time, requirements were often subtly varied according to the age, sex, and activity of rooms' occupants, and some authorities recommended as much as 30 cubic feet of fresh air per minute for each person. In the two decades that followed publication of the German experimental findings, fresh air requirements declined even more rapidly than they had climbed. By 1925 the consensus was that 10 cubic feet of outdoor air per person per minute should be supplied, the level forwarded by Reid almost a century before. Public health studies during the same period pointed out that no harm was done by recirculating air and that requirements of precise quantities of air supply were useless without consideration of the quality of that air. This resulted in the recommendation of percentages of air supply that might be provided through recirculation. Often as much as two-thirds of the required supply were allowed to be recirculated under what came to be know as the "effective air supply concept."[67]

Ventilation standards during the early part of the twentieth century accepted the germ theory of disease, and illness was no longer associated with atmospheres, vapors, gases, or miasmas. If contagion resulted from the transfer of microorganisms, that transfer was possible in almost any gaseous mixture. With disease prevention eliminated as a major objective of

most room ventilation systems, the regulation of temperature and moisture remained. For this purpose the presence of a specific number of occupants required that a room be supplied with a flow of air that remained constant in quantity, but could be varied in temperature according to fluctuations of temperature inside and outside the building. Sturgis's *Dictionary of Architecture and Building* commented in 1901 that "the only method in vogue previous to about twenty years ago was to close the register when the room was sufficiently warm; which of course not only cut off the heat supply, but the air supply as well, interrupting ventilation."[68] In order to correct this condition, the "mixing valve" was developed, with provisions for varying the temperature of air entering a room by mixing fresh cold air, outside air that had been heated, and recirculated warm air.

Research done in the 1920s and 1930s showed that temperature control was related to the esthetic consideration of providing an odor-free environment. Thereafter, in spite of the difficulty of determining levels of odor and the extremely subjective factors involved, the provision of an odor-free atmosphere was accepted as a central goal in the design of ventilation systems. Instead of carbon dioxide being employed as an indirect indicator of healthful air, the smell of air was taken as a valid measure of the physical comfort and social conformity of conditions within a room.

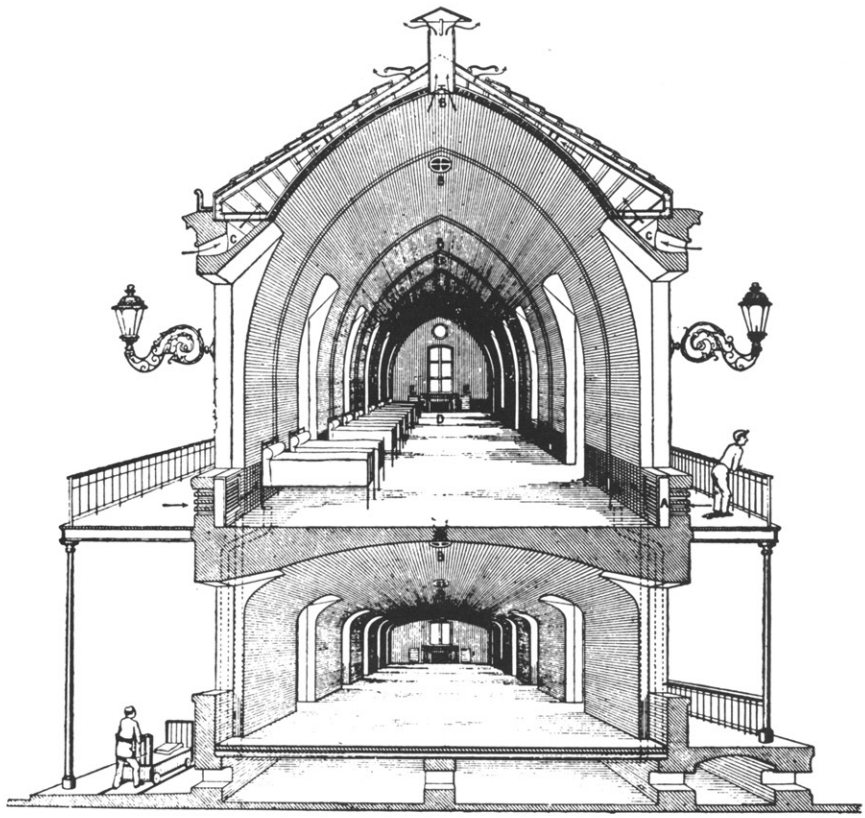
In recent times there has been a tendency to return to some of the precautions that were embodied in earlier standards for ventilation. Carbon dioxide and hydrogen are no longer considered threatening in normal circumstances, but radon, the gases from urea-formaldehyde, and other substances appear to be extremely dangerous in relatively low concentrations. "Organic effluvia" may not be feared today, but modern ventilation systems have on occasion scattered dangerous microorganisms and gases have caused illnesses.



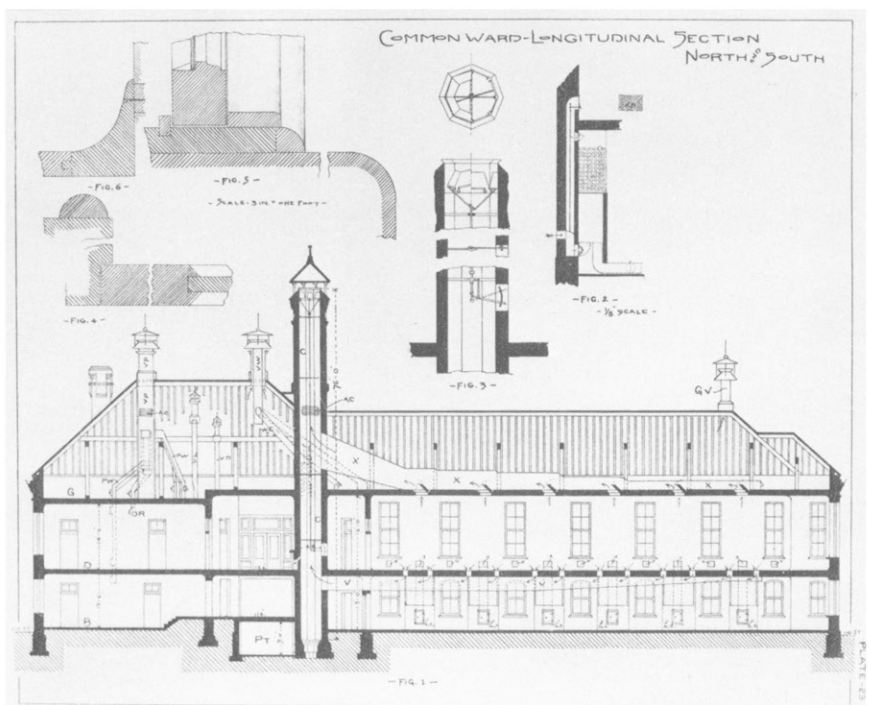
The specialized needs of some types of buildings assisted in the development of attitudes and devices that later found broader application. Because of their function, hospitals were a fertile area for experimentation. Louis XVI in 1786 instructed his architect to build new wards at Salpêtrière, Paris's major asylum for the insane, "so that the unfortunate women shall no longer be exposed to injury from the air." In the design that resulted, fresh air entered the door or window of each cell, rose through an opening in the ceiling, and was expelled through vented cupolas on the roof. This scheme was long used for hospital wards. By 1890 the type of ward design strongly recommended in France had beds arranged on both sides of a long, tall room with ventilators drawing out air at the top of an ogival ceiling (fig. 11.25).[69] Individual air intakes at floor level were assumed to surround each bed with an upward stream of ventilation, separated from the air moving around adjacent beds.

Florence Nightingale, adulated for her work in the Crimean War, favored wards of about 30 beds, a number that could be well cared for by a single head nurse. This led to a room 30 feet wide (it was believed that greater width between windows caused stagnation of air in the center of the room) and about 120 long, which avoided corners in which air did not move freely. In order that no air should linger overhead, the tops of windows

11.25 Before general acceptance of the germ theory of disease, hospital wards were designed to provide the best ventilation possible. In the Civil and Military Hospital, Montpellier, France (1884), the ground floor was a recreational area, and flues conducted air from beneath its floor to grilles beside the beds of the ward. Air entering at the eaves cooled the ceiling during summer weather. (C. Tollet, *Les édifices hospitaliers depuis leur origine jusqu'à nos jours*, 1892.)



11.26 In spite of the height of buildings at Johns Hopkins Hospital, many had only a single floor level for housing patients. The ground floor admitted air, which rose through grilles placed in the floor between the beds of the patients. Above the beds, air was led through the attic to a tall tower. (J. S. Billings, *Description of Johns Hopkins Hospital*, 1890.)

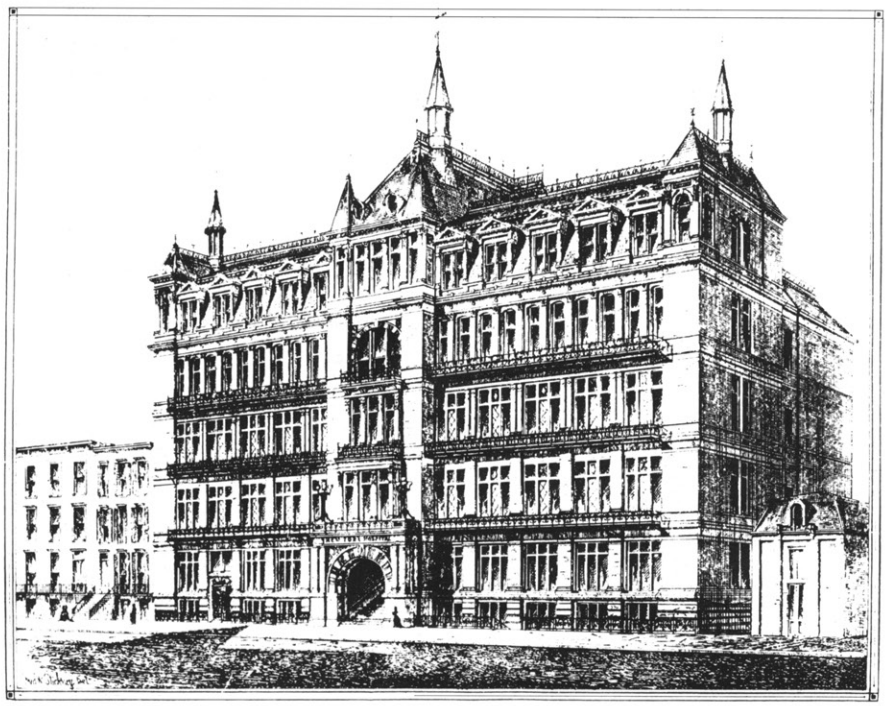


were to be near the ceiling, which was 16 to 17 feet high. Nightingale preferred heating and ventilating the ward by a fireplace in the center of the room. Her recommendations insisted on a plentiful supply and constant movement of air; however, she did not envision any method by which the circulation of air could be increased beyond that of an airy room.

In the United States, hospitals built for the Civil War had shown the value of a ward built rather like barracks, following most of the principles propounded by Nightingale, although often having twice as many beds. When the Baltimore hospital was founded by Johns Hopkins in the 1870s, the trustees asked for the recommendations of five experts. Of these, Dr. John S. Billings, assistant surgeon in the U.S. Army, was chosen to advise in construction of the hospital, for which J. R. Niernsee was architect.[70] The plan for Johns Hopkins Hospital consisted of a series of pavilions. The ground level of each pavilion was entirely devoted to ventilating and heating, the latter employing hot water (fig. 11.26). Air was delivered to the ward above through floor-level registers in each space between beds. In winter the air was removed through grilles in the ceiling. All foul air was led through ducts to an "aspirating chimney" that rose 76 feet above the fire that maintained its draft. In general, the effectiveness of such systems may well have been exaggerated. In the 1860s there were 220 tests made in the Munich Lying-in Hospital, where large chimneys were intended to exhaust air, and it was found that 58 percent of the time air moved in the desired direction, 25 percent of the time it was not in motion, and 17 percent of the time it went the opposite way.[71]

The New York Hospital, designed by George B. Post in the same period, was a five-story building as required by its urban location (figs. 11.27, 11.28). Its air movement was almost completely controlled by fans. Fresh air was admitted by grilles in the window sills, and air was exhausted through grilles high on the walls. Restricted sites required taller hospitals, as new institutions were built and old ones expanded. No longer could the ventilation of hospitals rooms be planned as simply as in one-story hospitals, where fresh air entered through the floor and rose through the roof. Channels, chases, and ducts were required, and the powerful force of fans was needed to draw air through them.

Like multistory hospitals, office buildings demanded special considerations. In early skyscrapers there were efforts to supply warm air through channels in the walls, but this method of heating proved impractical. The air had to travel so far that it was almost impossible to provide the required temperatures in every office; sound and fire could travel from floor to floor through the ducts; and the floor area occupied by such a heating system was unacceptable in buildings that demanded the most exacting utilization of their sites.[72] In many cases fireplaces were built in offices solely as outlets for air, their flues inadequate for actual fires. Hot water heating was the choice of most engineers, but steam was also used, either from independent boilers or as exhaust steam from boilers in the basement that operated engines, elevators, electric generators, and pumps. In New York the heating pipes of skyscrapers were usually concealed, but Chicago architects tended to expose them in offices and hide them only in the lower floors of very tall buildings,



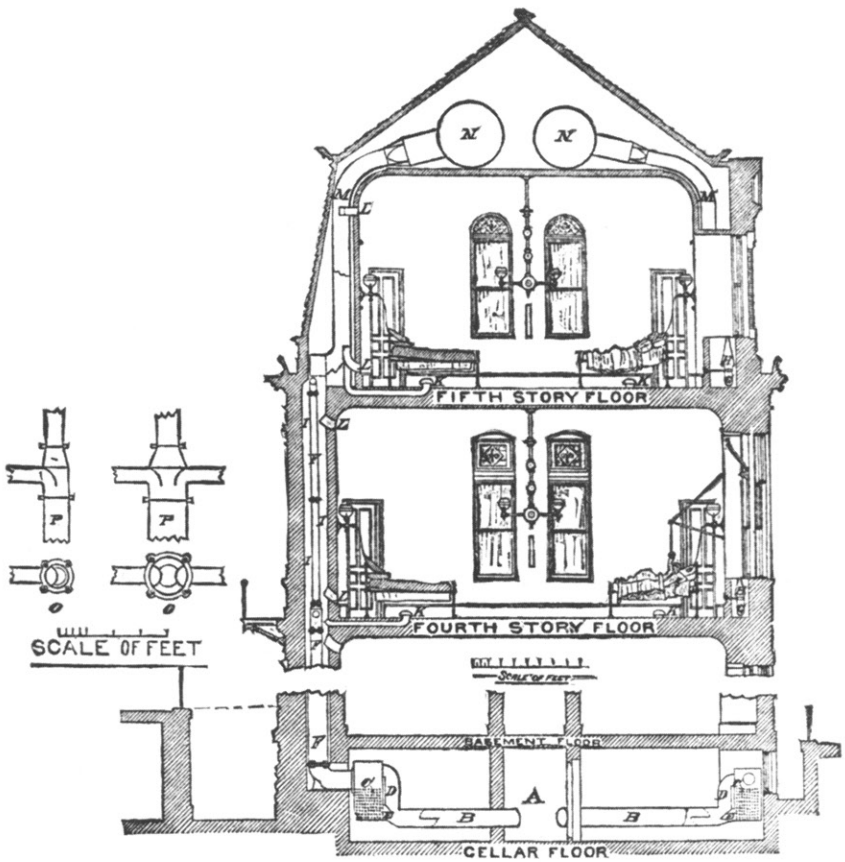
11.27 The extension of a street required that the New York Hospital be rebuilt, providing 200 beds on a very limited site. More typically, hospital construction had involved large sites at the fringe of cities, which permitted their having only one or two stories of nursing rooms. George B. Post's design (1875) established a pattern for the ventilation of hospitals that were a part of the increasing urban density. (*American Architect and Architecture*, 17 March 1877.)

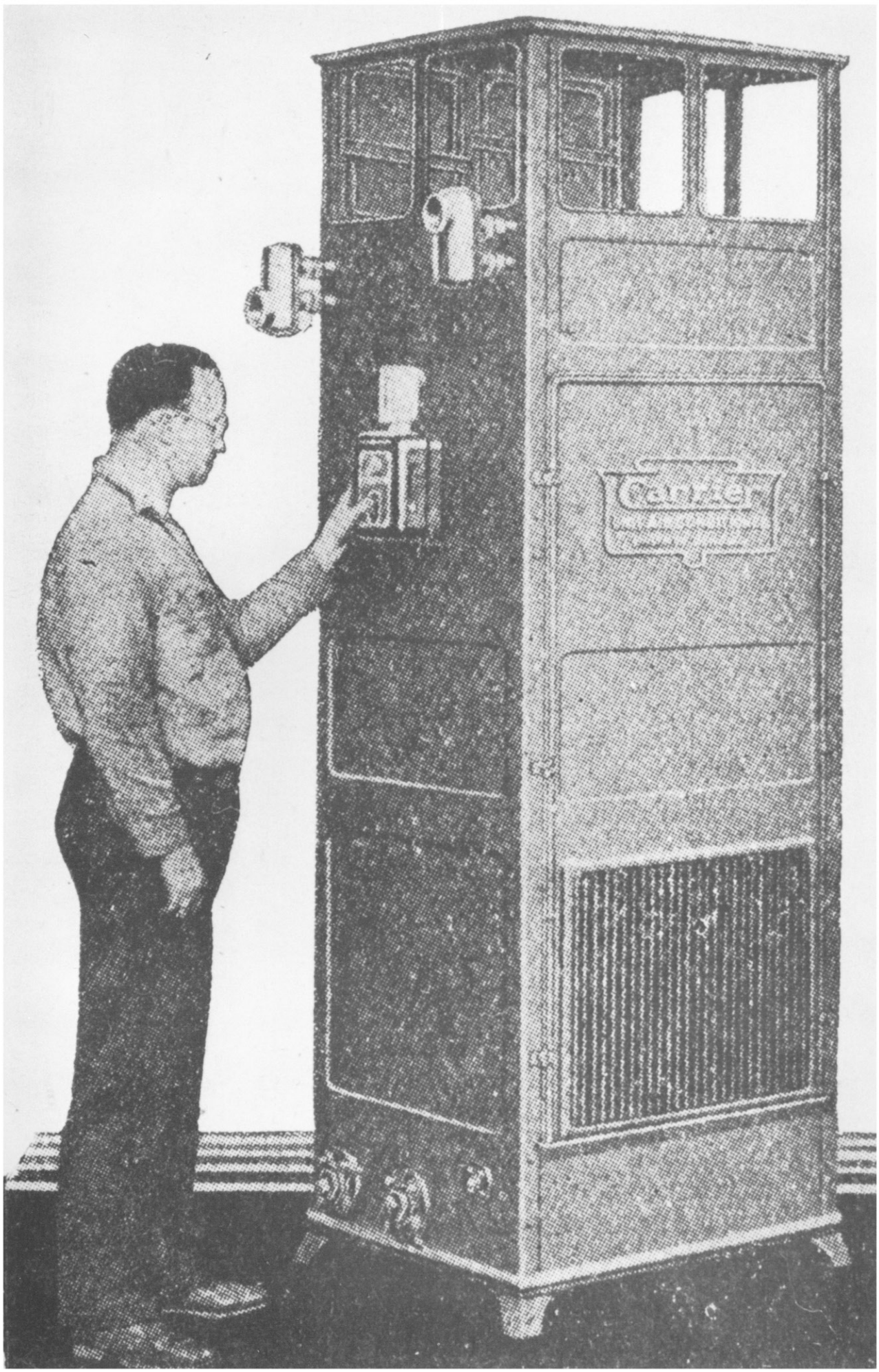
11.28 Ventilation problems of multistory hospitals in urban locales were solved through the introduction of mechanical ventilation. Fans in the New York Hospital brought in fresh air (*A*) and exhausted air from the attic (*N*). (C. Tollet, *Les hôpitaux modernes au XIXe siècle*, 1894.)

where supply mains were too large to be left visible and appearance was of greater concern.

The workings of a skyscraper's heating system were complex because of its dimensions, even if the basic design was relatively simple. The Equitable Life Building in New York, built just before World War I, contained 5,000 radiators. Its return riser was a mammoth tube 34 inches in diameter, which lengthened 8 inches when steam started flowing and the metal expanded.[73] Because the entire volume of a heated skyscraper served as a chimney with strong updrafts, air leaking into lower floors was a major heating problem. The installation of revolving doors lessened this problem and kept litter from being drawn into lobbies whenever doors were opened.

Sealed, well-insulated office buildings are today filled with equipment that provides high levels of illumination, computers generating heat, an assortment of business machines, and a host of employees. Heating has consequently become a different problem, always closely related to cooling.





Technics and Architecture

The Development of Materials and Systems for Building

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12

Air Conditioning

1834 Ice-making machine patented (Britain) by Jacob Perkins

1851 Dr. John Gorrie patents (U.S.) an air cycle compression ice-making machine

1889 Carnegie Hall, New York, provided with an air-cooling system using blocks of ice

1904 New York Stock Exchange installs a cooling system using ammonia as refrigerant

1906 Willis H. Carrier patents (U.S.) "Apparatus for Treating Air"

1928 Milam Building, San Antonio, Texas, a milestone in air-conditioning office buildings

Introduction of the room air conditioner

12.1 When the ice tested thick enough for harvesting, ice drills were used to make holes in which saws could be inserted. Once cut, the blocks of ice were floated along channels to the shore. Teams of horses drew them up ramps and into the ice house, where they were laid in place with thick layers of sawdust. (*Scribner's Monthly*, August 1875.)

12.2 By the end of the nineteenth century, ice harvesting had become industrialized, far from the simple methods by which countryfolk had preserved ice from their farm ponds. The vagaries of winter weather and increasing pollution of lakes were powerful restraints on industrial development. (*Appleton's Cyclopedia*, 1880, 2:130.)

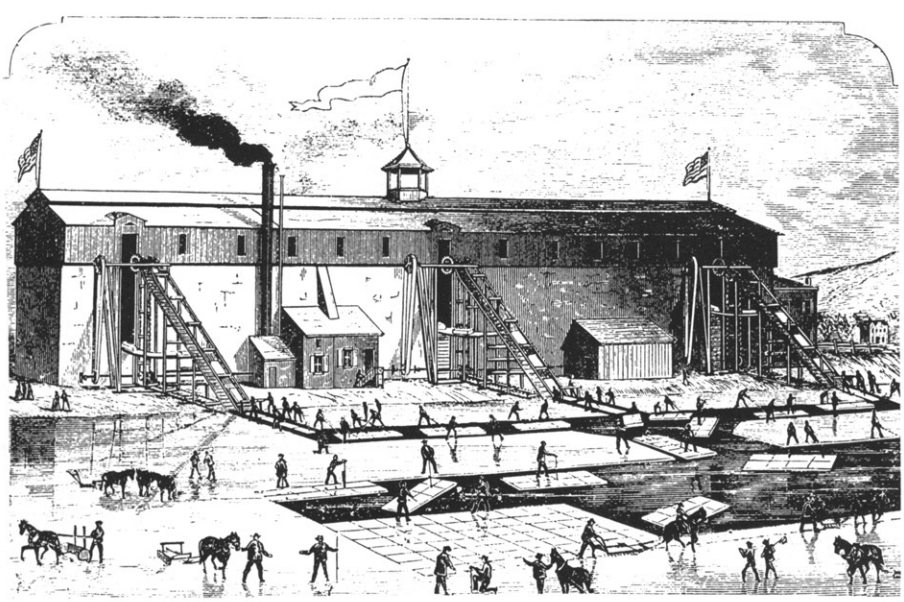
Throughout the fourteenth century the northern hemisphere cooled appreciably, so much that icebergs appear to have interfered with the Viking explorations of America. Some scholars find insufficient evidence to justify calling a long period between 1579 and 1880 the "Little Ice Age." However, cold periods occurred in about a quarter of the seventeenth century, and in eastern North America and western Europe 1816 was known as a year without a summer. In America there was a greater annual fluctuation of temperature than in most parts of Europe. Winters were bitterly cold in much of the area that was first settled, and summers could be blistering hot. Food was difficult to preserve. Smoking, corning, and drying were common methods of keeping food, and in hilly regions there might be a cool spring over which a shelter could be built as a place to chill milk and other perishables. In northern parts of the United States, icehouses were erected to store the winter's bounty for the summer days ahead. Only 12 designs for icehouses were granted patents in the United States from 1790 to 1873, and all those were awarded in the last 25 years of that period. Apparently European interest may have grown during that time, as witnessed by a German publication of 1864 in which the icehouse has a triple wall with the space between two of the walls large enough to hold barrels of beer at an intermediate temperature.[1]

In 1806 the brig *Favorite* sailed from Boston Harbor with a cargo of 130 tons of ice that Frederic Tudor had cut from a pond on his father's farm near Saugus, Massachusetts. Its destination was the island of Martinique, where ice was needed to cool victims of a fever epidemic. Unfortunately, the scorching sun of the Caribbean melted much of the cargo and Tudor's venture proved a financial failure. Two years later another shipment—this time to Havana—was equally unprofitable. Tudor began again after the War of 1812, and competitors joined him. In 1816 only five cargoes of ice were exported from Boston harbor, which was destined to dominate the American ice trade, and

these shipments totaled 1,200 tons. Thirty years later the cargoes numbered 175 and the tonnage was 65,000. The range of the ice trade had by then extended from the West Indies around the Horn to Asia and Australia.[2] Most of this ice was intended to tinkle in the glasses of the wealthy, some was used in treating fevers, and much was purchased to refrigerate meat or maintain the temperature required to brew lager.

In the northern areas of the United States, local enterprises quarried and sawed blocks of ice from ponds and floated them along channels to points where horses could draw the blocks ashore. There they were loaded for transportation to a pit or an icehouse (figs. 12.1, 12.2). Often the harvesting of ice was an off-season activity of logging companies, which already had sleds and draft animals and produced the sawdust that was needed to insulate blocks of ice as they were placed in storage. Lumber mills, which had long contended with dangerously flammable piles of sawdust and shavings, now found buyers for those materials. In 1857 almost 100 wagons and about 150 horses were used to distribute 60,000 tons of ice to users in Boston and its environs.[3] Fishing boats began to set sail with their holds half-filled with ice to refrigerate their catch and keep it fresh for market. Passenger ships began to carry refrigerated meat, instead of slaughtering live animals during a voyage. Typically, double-walled icehouses, as developed by a Boston ice merchant, were filled by first spreading 6 to 8 inches of sawdust over the floor. About 4 inches of sawdust was placed in the spaces between blocks of ice and the icehouse walls and, when the building's capacity had been reached, 1 or 2 additional feet of sawdust were scattered over the top of the ice.[4] The profitable relationship between logging companies and the ice trade was equaled by that of urban concerns that used wagons and horses to supply coal in winter and ice in summer.

Before the Civil War, the city of New Orleans annually received some 50,000 tons of ice from Boston alone. In satisfying this demand and pricing the ice, the vagaries of winter weather always played a prominent role. Relatively warm weather in the northern states could reduce the winter's harvest and greatly increase the prices paid for ice during summer months.



12.3 In his 1851 patent, John Gorrie declared that his ice machine would "accomplish my object with the least possible expenditure of mechanical force, and produce artificial refrigeration in greater quantity from atmospheric air than can be done by any known means." Gorrie died only four years later, frustrated in his efforts to obtain sufficient financing to develop his invention. (U.S. Patent no. 8080.)

12.4 James Harrison, an Australian journalist, succeeded around 1856 in developing an ether compression machine that was probably the first mechanical refrigeration system used in brewing. However, he did not succeed in his goal of finding a means of shipping the plentiful mutton of the Australian plains across the Indian Ocean to England. (*ASHRAE Journal*, July 1969.)

According to a grocer in Tennessee, shipments from the Northern Lakes Ice Company in La Porte, Indiana, lost as much as 40 percent of their weight while traveling over 600 miles in railroad boxcars.[5] Waste in storage and shipping often made natural ice costly, but it was a necessity for certain developing industries. By slaughtering animals in the West and shipping dressed meat in refrigerator cars, meatpackers could reduce freight charges, eliminate the cost of feeding in transit, and avoid the loss of animals' weight during shipping. Brewers, abundant after the German immigration of the 1840s, required low temperatures in order to regulate their preparation of lager. In some areas near metropolitan centers, natural ice continued to be cut and sold as late as 1919.[6]

Joseph Black, a young Scottish chemist, in 1760 evolved the theory of latent heat, which states that heat is absorbed as a liquid evaporates and heat is released by condensation of a vapor. This discovery was vital in the development of the steam engine, but it found other applications. More than 20 years later a Scottish physician, William Cullen, devised a machine in which air was pumped out of a closed vessel that contained water, the reduction of pressure increasing evaporation and thereby causing the water to freeze. It is these two phenomena, the latent heat of vaporization and the effects of pressure, on which refrigeration systems are based. In compression refrigeration, a liquid with a low boiling point is mechanically compressed before being released through a valve; in absorption systems two fluids (often ammonia and water) are heated until one evaporates and pressure rises to cause its condensation, then that fluid is released through a valve. Until the development of Freon in 1930, much attention was given to the characteristics of different refrigerants and the dangers of toxic and flammable materials escaping from the system.

By the nineteenth century, there was no lack of scientists and dabblers prepared to speculate about the methods by which cold might be produced mechanically. An American, Oliver Evans, proposed one in his book *The Abortion of a Young Steam Engineer's Guide;* a Scot described an absorption system that used sulphuric acid; and an Englishman gave demonstrations of an ice-making device that also employed sulphuric acid.[7] None of these forerunners were to have so much influence as an invention patented by Jacob Perkins, an American engraver and inventor who had settled in London to promote his method of printing currency in a manner that discouraged counterfeiting. Perkins's British patent of 1834 for ice making involved a chamber in which ether was compressed and evaporated according to the discovery of Cullen, and through that chamber snaked a system of pipes in which brine circulated and was cooled to about 5° F. From the evaporator, the brine flowed to another chamber containing boxes filled with water. As the water was