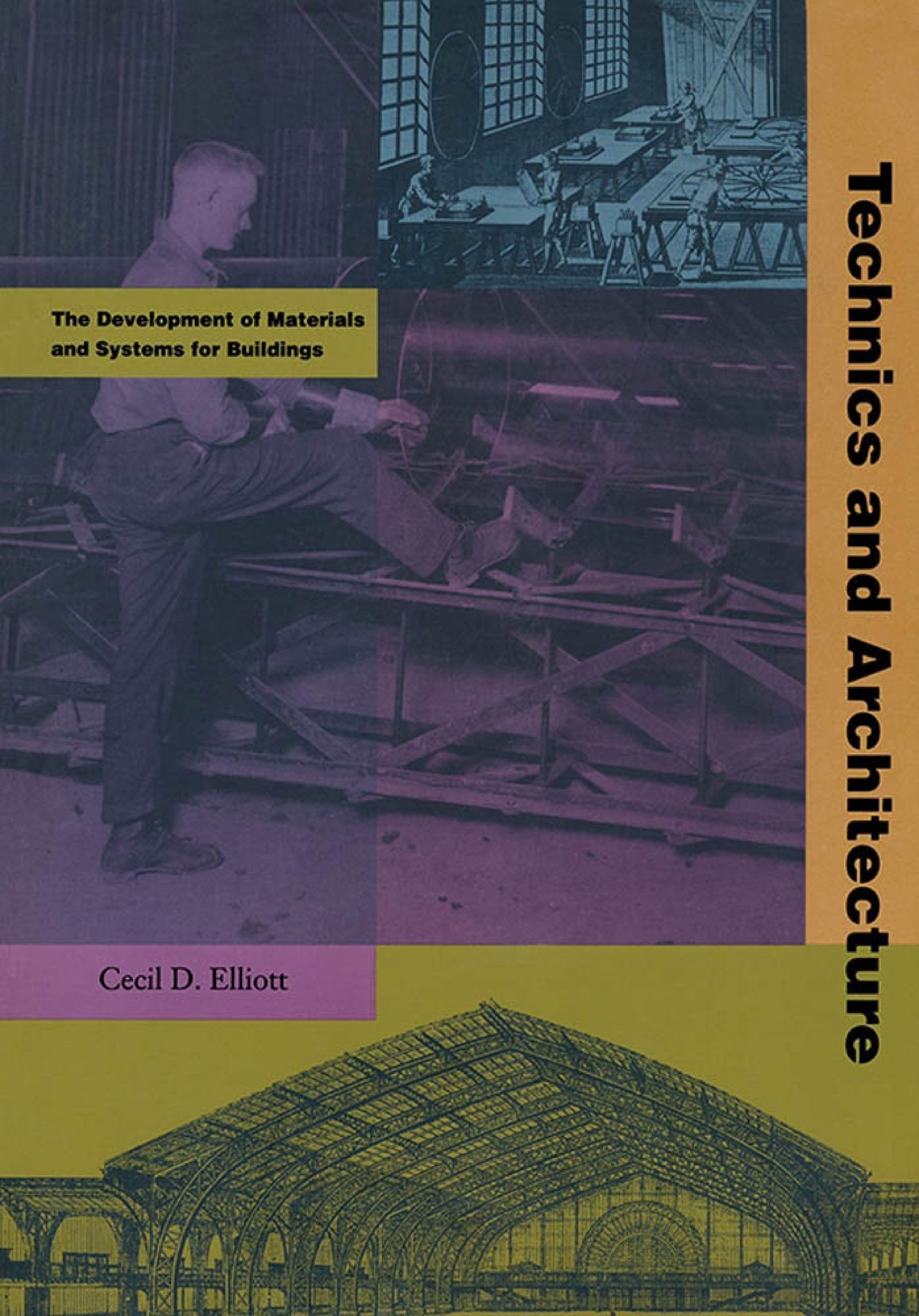

Technics and Architecture

The Development of Materials and Systems for Buildings

Cecil D. Elliott

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Preface

This study gathers together stories of the production of building materials and the development of building equipment and other systems. These are the media in which architects work. They constitute the array of possibilities from which architects, builders, and investors make the choices that largely define the nature of a building, and because they are on the whole pragmatic departures, successful new materials and systems soon become accepted as necessities, elevating the standards of performance by which buildings are to be judged.

The accounts that follow focus on the period of the Industrial Revolution and the times that came after, with introductory descriptions of earlier events. Much of the narrative centers on England, where mechanization first flourished. Later, in the nineteenth century, leadership shifted to the United States, where the force of expansion generated opportunities for experimentation. Emphasis has been given to the general adoption of systems and materials, and "firsts" have been neglected because such claims are as a rule questionable.

The text has been divided into two parts. The first groups seven categories of building materials in an order that is roughly chronological. The second discusses nine systems of building functions, including five developed to improve comfort and convenience and four that embodied the technical and scientific knowledge of the period when they were developed. In some cases different chapters may share a subject, treating separate aspects. For instance, terra-cotta fireproofing is discussed both in the chapter devoted to the manufacture of that material and in the chapter dealing with problems of fire protection. Structural engineering related to a specific material (iron, steel, or reinforced concrete) is treated as an aspect of that material's development and use, and general structural principles are considered in a chapter that reviews the foundations of structural theory and practice.

Each of these stories has its own character. In some cases, governmental and economic influences determined the outcome; in others, scientific discoveries or the growth of other industries may have controlled events. The distinctive characteristics of each story have been stressed, relinquishing a uniformity of treatment for the emphasis of individual features.

Beyond the matters discussed in this volume, there remain many subjects related to the construction industry, laborers in building crafts, the use of machines in construction, and other aspects of building and architecture. It is hoped that this volume may encourage scholars' study of such topics.

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Local and state historical organizations (too many to mention individually) delved into their files and provided much of the information that expanded my understanding of places and people.

In preparation of the manuscript, invaluable assistance was given by Ronald L. M. Ramsay, who generously shared with me his knowledge of research techniques and material from his own files; Frances Fisher, who gave encouragement and commented on several chapters; Dennis C. Colliton, who commented on the chapters about elevators and brickmaking; Joel B. Goldsteen, who commented on the chapter on cements and made suggestions about organization; Bernard A. Nagengast, who gave expert advice regarding the chapters on heating and air conditioning; Earl E. Stewart, who commented on the chapter related to acoustics; and George E. LaPalm, who commented on the chapter on structural engineering. Errors of fact, interpretation, and omission remain the author's responsibility.

I am also indebted to students of the Department of Architecture and Landscape Architecture, North Dakota State University, with whom I had the opportunity to discuss these subjects in seminars.

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Introduction

The architecture of the Industrial Revolution, from the middle years of the eighteenth century to the last of the nineteenth, is best identified as Romantic. A variety of terms have been coined to mark subdivisions of this period's stylistic attitudes, using the term "Revival" in some cases and the prefix "Neo-" in others, but always adding the designation of a previous style of architecture. (Art Nouveau, at the very end of the nineteenth century, is perhaps the sole exception to this tendency.) From the start of the Renaissance to World War II, the dominant stylistic theme in architecture was a reliance on the past, the extent of historical accuracy varying according to the patronage, physical requirements, and architectural talent under which a project was executed. Until the middle of the eighteenth century, European designers, both Renaissance and Baroque, adapted ancient motifs with considerable freedom, and their styles themselves later became models for the eclecticism of the nineteenth century. Each of the Romantic movements—revisitations of the Greek, Roman, Romanesque, Gothic, and even more exotic styles—responded to current ideals. Newly established representative governments (for the Industrial Revolution was also a period of political revolution and theorizing) echoed the forms of Greece and Rome in their buildings; and religious groups, according to their outlooks, chose between the perceived rationality of classical styles and the emotionalism of Gothic.

The concurrence of the Industrial Revolution and Romanticism is understandable if one accepts the historical realities. The innovations of industrialization, so stunningly compressed and dramatized in history books, were slow to be accepted and operated throughout any industry or any country. During his lifetime the average citizen of the western world in the eighteenth and nineteenth centuries had contact with only a few significant technological advances, and these were accepted as merely sensible solutions to practical problems, not part of a juggernaut of industrial development. For instance in 1880, some four generations after the first steamboat, about three-quarters of the world's shipping capacity was still under sail. Many of the innovations that proved to be most influential were at first viewed as curious experiments, having questionable value under realistic conditions.

The reality of Romanticism is similar in that it was to some extent a part of the literature, painting, music, and architecture of all periods, and its dominance during much of the eighteenth and nineteenth centuries developed gradually in the company of considerable social and political change. While classicism had espoused the cause of simplicity and the evolution of acceptable forms of expression, Romanticism encouraged individualism, imagination, and emotion, accepting even fear and morbidity as beneficial experiences. Such preferences fostered an appreciation of variety and change, and the drama of invention was to the Romantic often more attractive than its results.

Our histories of architecture correctly stress the importance of milestone buildings that were far in advance of the normal course of design and construction; reading them, one might almost be persuaded that the innovations of Louis Sullivan or H. P. Berlage were quickly, enthusiastically, and widely accepted as models by the architectural profession and its clients. In truth, new ideas such as these prospered among narrow ranges of patronage and professional practice. The rate at which technological advances were adopted was far more rapid for factories, office buildings, department stores, and other types of buildings that were blessedly free of professional or public preconceptions about architectural style than it was for the more traditional types of buildings. Later in the twentieth century the impetus toward nonhistorical designs and the incorporation of technological advances was severely limited by the twenty-year hiatus of the Great Depression, World War II, and the years of painful postwar recuperation.

It would be convenient, but only somewhat accurate, to attribute twentieth-century changes in architecture to the influence of technology as it was applied to buildings. Architecture is a complex art having many masters. A building is at the same time an object, an investment, and a cultural and personal expression of beliefs. Any change in the way buildings are built or the way they look must be tested against a variety of standards, their relative importance being somewhat different for every project. This truism explains why certain technological aspects of architecture have been readily adopted and others have been long delayed. For instance, elevators were a vital factor in the economic and social changes related to the great sweep of urbanization, and therefore elevator technology was immediately accepted and quickly developed. No similar urge spurred the development of a more rational system of plumbing and waste handling.

Often the mood of historicism was superficial. The choice of a Greek temple as model did not necessarily rule out grafting a dome or spire onto a design, and with up-to-date construction techniques Gothic naves often acquired proportions that bore limited relationship to those of the buildings they emulated. New technologies intruded gently because historical accuracy and consistency, not prime criteria of Romanticism, were generally less valued than the evocation of appropriate sentiments.

Nearly all buildings are singular designs, though with pronounced similarities to other buildings of the same purpose, place, and period. The individuality of projects has effectively limited the extent to which industrialization has been applicable to architectural construction. In the early eighteenth century, the process of assembling a building might well begin on the site with preparation of the clay and kiln that would produce brick for the walls. Timbers for trusses would be cut, mortised, and drilled by the workmen who would set them in place. Today such elements of the construction will have been largely prepared before they are brought to the site for assembly into the final structure. Although craftsmen still work to fit and fasten in place the parts of a building, the nature of their work has gradually changed as industrialization and the concomitant standardization have increased the relative completeness of elements that are brought to the site of construction. At the same time, the Industrial Revolution and the revolution in transportation that accompanied it reduced the architectural significance of a region's own materials. Local differences in the prices of materials still exerted appreciable influence on selections, but their significance diminished as decades passed. Climatic differences have become less important, because equipment and materials have been developed to ameliorate the effect of external conditions on buildings' interiors, and cultural and economic exchanges between nations and places have acted to reduce the differences between buildings in different settings. Good or bad, office buildings throughout the world are much alike, government buildings have been similar since the Classical Re-revival at the start of this century, and even residences are moving toward greater similarity.

The modern movement in architecture, which blossomed in the 1920s and bore fruit after World War II, has been on the whole more eager to utilize new materials and incorporate new systems than were the Romantic historically based fashions that came before. In the chapters that follow, the reader will note that in the majority of cases the most advantageous improvements in the manufacture of materials and in the quality of systems for buildings were achieved in the last quarter of the nineteenth century and the first decade of the twentieth century. Since that time the acceptance and application of those advances have increased, and in many cases the need for further fundamental development has become apparent. At present, architects work with a relatively stable palette of technological development, seeking viable responses to social and economic functions and awaiting a revival of inventive enthusiasm that may improve the art's technological capabilities.

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Materials

The materials that have been used to construct buildings during the last three centuries were already present in ancient and medieval times. The change, in essence, has been largely in the development of mechanized methods for manufacturing them and in the networks of commerce that have made raw materials and finished products available. Early technological advances improved the tools and methods used in the preparation of building materials, but such changes often resulted (as with early advances in glassmaking and stone quarrying) in little more than transferring traditional handwork procedures to the operation of machinery. The more startling advances in the western world's material accomplishments were rooted in the enlargement of scale, which extended markets and challenged industrialists with a scale of operation that had previously been available only to some political leaders. Industrial "empires" and competition (so fierce that terms of warfare were often used to describe it) in the late nineteenth century found fitting reward in the medals presented to competing manufacturers at the international expositions of that period.

Although the use of a material in building construction provided the major market for few industries, this application profited from the advances for which other uses provided the stimulus. In addition to its fostering the expansion of industrial activity, transportation required mammoth constructions. By the end of the eighteenth century the tonnage of European shipping was about five times as great as it had been two centuries before. To attend these vessels, it was necessary to expand and improve harbor facilities. The establishment of railroad lines required construction of bridges and viaducts along routes of remarkable length. These developments, along with the growth of cities between which goods were carried, stimulated the production of many of the materials needed for building construction. Such activity was by no means continuous or untroubled. In England the two waves of railroad construction were divided by six years of desperately hard times, the so-called "Hungry Forties," which were reflected in a reduction in brick production (then a fair indicator of building activity) of almost one-fifth. But this was much smaller than the one-third reduction of brick production that occurred at the beginning of the Napoleonic wars, when construction workers joined the military forces and the prices of building materials rose sharply.

Although construction itself lagged far behind factory industries in its mechanization and industrialization, building activity thrived. Between 1875 and 1907 in Germany, employment in construction grew from 10 to 16 percent of the total national work force. The massive movement to cities increased population densities there, and merchants and manufacturers became the dominant patrons of building construction. In England, public expenditures and the interest rate on government bonds decreased radically around 1820 and remained relatively low during the remainder of the century. During that period construction work and architectural commissions rose. It appears that buildings, whether commercial, industrial, or residential in function, came to be recognized as alternative investments. Frugality and the demand for more intensive and profitable use of sites, at the same time, changed the character of buildings and the materials of which they were made. On one hand, new and improved materials made it possible for buildings to satisfy needs that were new to the period, such as larger spans and taller structures. On the other hand, for more traditional functions it was possible to make these materials conform to the standards of propriety and taste to which bourgeois patronage aspired. This meant that architecture was soon forced to contend with opposing forces: the material nature of the media in which it worked and the visual expectations of the art, whether the latter were founded on historicism or cubistic abstraction.

As animal power gave way to water power and steam power, the simple procedures of local manufacture for a regional market were necessarily superseded by those of larger work forces, sufficient to produce enough goods to justify the required investment in equipment. At one extreme, the tightly knit work groups of glasshouses isolated in forest land became blowers' teams, reporting to the factory when a batch of molten glass was ready for their work to commence; under full mechanization, glassworkers became machine operators and supervisors in large factories. At the same time the casually assembled crews brought together for such seasonal operations as brick kilns became regularly employed work forces, once mechanized preparation of the clay permitted more continuous operation of brickyards.

For those materials manufactured with the use of heat, a critical factor was the economical utilization of fuel, which was often the principal determinant of price. Wood and charcoal, the most ancient fuels, became too costly as forests were devastated for use in buildings and ships. The specific locations of coal, petroleum, and natural gas required the location of factories where fuel was to be found or at points to which it could easily be brought. Nevertheless, profitable manufacturing required the most efficient possible use of fuels. This problem was common to all industries using furnaces and kilns. Efforts were made to improve processes by eliminating the intermittent heating of furnace masses and utilizing the heat of escaping gases. Such improvements were usually expensive to institute and their importance varied among industries according to the relative significance of fuel costs, the level of competition present, and economic trends. In many cases, the adoption of new fuel-saving methods was delayed because of the reluctance of factory owners to make the large investments that were required. In most industries it appears that the effects of competition were dulled in the late nineteenth century by localization of markets, the imposition of tariffs, and price-fixing manipulations by groups of manufacturers. Scientific knowledge became increasingly important as the factories producing building materials grew in size and international competition intensified. Mixtures and methods that were part of a craft's heritage and innovations that had been discovered by chance gave way to scientific analysis. The development of metering and testing equipment permitted an increased accuracy in controlling production and gauging the quality of the material produced, and advances in the scientific understanding of heat permitted more efficient use of fuel.

Architects' use of materials during this period followed three patterns. Industrialization of the production of some materials, such as masonry, wood, and glass, did little to alter their nature and quality but increased their availability. For others, terracotta and concrete, their early use as substitutes for traditional materials soon waned. The most dramatic influences were structural materials, iron, steel, and reinforced concrete, which permitted the development of new building forms responding to changed needs.

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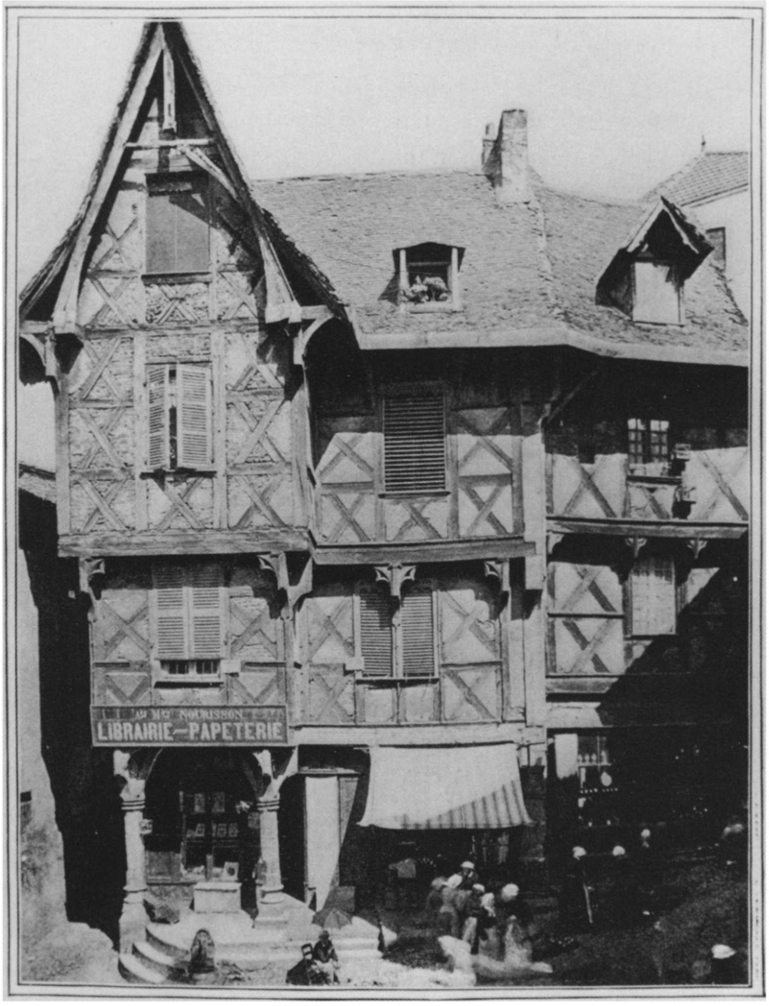
Wood

1777	Circular saw patented (Britain)
1832	Balloon framing introduced in Chicago
c. 1850	Circular saw first employed in processing lumber
1860s	Great Lakes area becomes center of the U.S. lumber industry
1867	Rotary veneer lathe developed
1870s	Double-edged axe introduced
	Peak of investigations of chemical preservatives by U.S. railroad interests
1880s	Saws with raker teeth used in felling
1883	Completion of railroad to Puget Sound opens forests of northwestern U.S.
1884	Production of three-ply chair seats in Estonia
1890s	"Hot ponds" make year-round operation possible for sawmills in North America
c. 1900	Resawing introduced
1905	Softwood plywood displayed at Lewis and Clark Expedition Centennial
1933	Synthetic resin glues produced in Germany

European life until the nineteenth century was largely based on the use of wood and the exploitation of the continent's vast forest lands. Wood provided fuel for industrial and household purposes, raw material from which tools and utensils were fashioned, and timbers from which carts, ships, and buildings were assembled. As the European population grew and spread toward the deep woodlands of the north, trees were felled in increasing numbers. Wood and charcoal had provided heat for Greek smelting and other crafts, and charcoal braziers heated Greek buildings when the sun's rays were not sufficient. Greek ships of trade or war required much timber, and when the Delian League was established in the fifth century B.C. to protect Greek interests in the Aegean Sea, the city-states were pledged to contribute a fleet of about three hundred warships. By that time so many trees had already been cut that the Greek landscape had been altered significantly. Indeed, the Greek city-states had introduced restrictions designating those processes for which wood or charcoal might be used as fuel. Several centuries later, Rome was confronted with a similar problem. Forests near the city were so depleted that it was necessary to obtain wood from almost a thousand miles away. By the fourth century A.D. the needs of Rome were served by a fleet of "wood ships," which brought timber from France and North Africa to the port of Ostia, from where it was moved upriver to Rome.



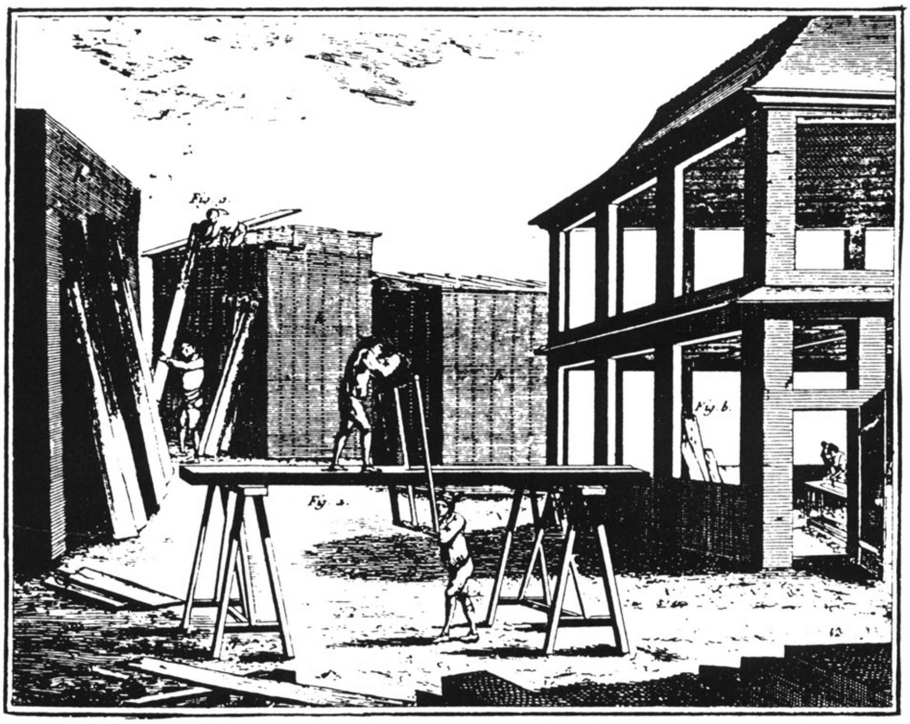
Although the amount of wood used in the construction of buildings was certainly less than that used as fuel and probably less than that used in ship building, deforestation made lumber more expensive, especially for the heavy timbers needed in roof construction. In the sixth century B.C., Greek temples, which had previously been of wood with terra-cotta surfacing attached, began to be built of stone, except for the roof construction and ceilings, which were still made of wood.[1] In later centuries, Roman settlements were constructed in northern Europe, where the forests still grew dense and wood was plentiful. Remains of the structures testify that there was a plentiful supply of seasoned timber, and the skill with which it was assembled is evidence of the efficient organization of the Roman army and the variety of iron tools that were available at that time.[2]

Accounts of medieval building projects often begin with descriptions of bands of carpenters going into a forest to fell the oaks that would be used. This meant that the lumber might not be properly cured by the time it was used, with the accompanying probability of warpage, but the slow progress of work on large projects in that period often provided for them a degree of curing during construction. In the fifteenth century, average sizes of wood framing in England would be about 13 by 11 inches for principal posts and 10 by 7 inches for joists spaced with around 8 inches between them (fig. 1.1).[3] Improving craftsmanship and rising costs of lumber reduced those formidable dimensions so that after the Great Fire of London (1666) joists were more likely to be 7 by 3 inches, less than half the cross-sectional area of earlier times.

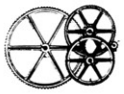
When Abbot Suger required 12 beams of extraordinary size for one of his projects, his carpenters and those he consulted in Paris knew of no French forests in which timbers so large could be found, and the abbot and his aides are said to have searched the woods until suitable trees were discovered.[4] In England an exhaustive inquiry was required to locate the long timbers required for construction of the lantern at Ely Cathedral, for by that time, the middle of the fourteenth century, lengths greater than 30 feet were rarely available.[5] In early times structures of appreciable size were built by the crown, the greater nobles, or the church, and each of these classes of patrons usually possessed broad forests from which trees could be selected for the projects that they might undertake. As building came to be a more widespread activity and English forests were more rapidly depleted, there arose a trade in timber, shipping fir and oak from the Baltic ports to England. This commerce brought timber principally from the Hanseatic ports of Danzig, Riga, and Memel and exchanged it for English cloth. Oak was the wood most highly prized for English ships and buildings, whether built for government or for trade, and the forests upriver from Baltic ports held rich stands of oak, as well as fir and pine. The forests of Sweden and Norway were an additional source of timber, a source that grew to be so important that in the seventeenth century it was said that "the Norwegians warmed themselves by the [Great] fire of London."[6] From German forests, logs were floated down the Rhine to be shipped from Dutch ports.

To prepare lumber for use in construction, medieval carpenters (for in most areas carpenters undertook the work from felling the trees to completing the joinery) rough-hewed the logs with an adze or split the wood with iron wedges and mallets. It was usually after the squared logs were removed from the forest that pit sawing took place. For sawing, a log or a riven half-log was raised on trestles or laid on the ground above a pit. The line to be followed in sawing was marked by a chalked cord and a pair of sawyers, one standing atop the log and another beneath, used a two-handled saw or a frame saw in which the blade was stretched within a wooden rectangle (fig. 1.2). The saw

1.1 As in this fifteenth-century house in central France, when medieval buildings were made of wood, massive timbers occupied much of the exterior wall surface, leaving small interstitial areas to be filled with masonry or other materials. Connections, which were mortised and pegged, required that the timbers be large. (*Architectural Record*, April 1900.)



1.2 In this view of an eighteenth-century lumberyard, a frame saw is used to divide a plank laid across trestles. Most of the energy for sawing in this manner was provided by the lower sawyer, and the worker above was responsible for guiding the cut along a chalked line. (Diderot, *Encyclopédie*, 1762–1777, "Menuiserie," plate 1.)



1.3 A sixteenth-century design for a hand-cranked gang saw. In this period, drawings of mechanical inventions were often published to demonstrate the principles involved; the inventions may never have been actually constructed and operated. (*Iconographic Encyclopedia*, 1889, vol. 6.)

cut as it was pulled downward by the worker who stood, covered with sawdust, in the bottom of the pit. Pit sawing, or similar methods, is still practiced today by residents of some of the least developed regions of the world.

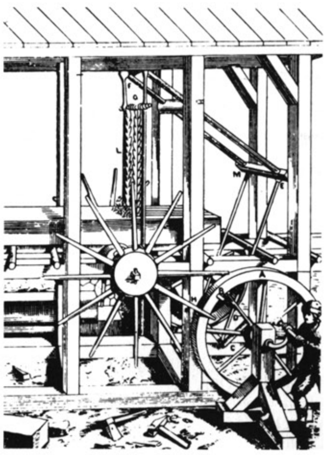
The work of the pit sawyer was easily mechanized. During the sixteenth century, sawmills powered by water or wind were erected in Norway, Holland, and some Baltic areas.[7] An estimate at the end of the eighteenth century said that "one mill, attended by one man . . . will saw more than twenty men with whip saws, and much more exactly," but it is difficult to estimate the financial advantages because one must consider the relative wages of the different sorts of workers and the amount saved by not shipping wood that would become useless sawdust. Apparently, English pit sawyers were apprehensive about changes that might result from mechanization. Water-powered mills for other purposes were built in England from the thirteenth century, but there were few sawmills, although many travelers gave detailed accounts of those they had seen on the Continent. In the sixteenth century, an increase of the English birth rate caused a population explosion, and unemployment among unskilled workers accompanied migration from rural districts into towns. In the early seventeenth century, a young traveler wrote his father an enthusiastic description of a sawmill he had seen in Germany but closed with a comment that he "would recommend the use of mills to saw timber in England, were it not that it would hinder the employment of poor men."[8] The public's fear of the social results of technological change persisted. As late as the 1760s, when a prosperous timber merchant built a wind-driven sawmill, a mob of irate pit sawyers attacked and pulled it down.[9]

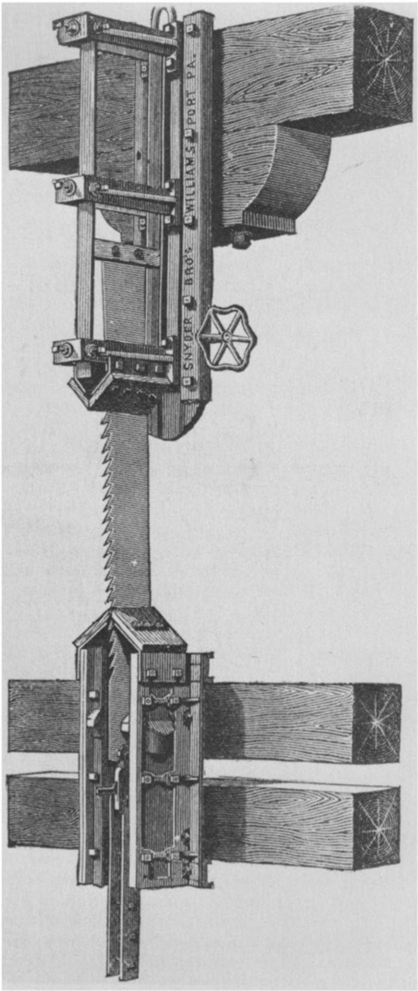
The earliest sawmills of note were based on a turning source of power (whether from wind or water), a crank that converted that rotary motion to a linear motion, a rocker arm attached to the vertical frame that held the sawblade, guides in which the frame moved, and perhaps a spring system (sometimes formed by a bent piece of wood) that would return the frame after the completion of each stroke (fig. 1.3). In addition, a system of weights or rollers was required to move the timber forward and maintain its contact with the saw blades. The frames of these saws were heavy, which limited the speed with which they could be operated. In nineteenth-century Mississippi, 120 strokes per minute was the greatest speed at which a sash (or frame) sawmill could run. This allowed the mill to saw between 3,000 and 5,000 feet daily, with a kerf somewhat greater than a half-inch.

The muley saw—its name derived from the German word for "mill"—was a later mechanism using vertical reciprocating action. Dispensing with the heavy frame of previous saws, the blade of the muley saw was mounted at top and bottom in a manner that allowed adjustment according to the size of the logs being sawed (fig. 1.4).[10] The greatest advantage of the muley saw was the smoothness of its cut, its kerf being somewhat narrower than that of previous saws. (The width of saw kerf, which set the amount of sawdust produced and hence largely determined how much wood would be wasted, mattered little in the early spendthrift period of a forest's exploitation, but as the wealth of wood dwindled lumbermen became acutely concerned about narrowing kerfs.) The principal disadvantage of the muley saw was its speed, which was no greater than that of the saws introduced earlier.[11]

The gang saw resulted from placing several blades together, so that a series of boards could be cut with one pass of a log through the saw (fig. 1.5). It was the first of a series of devices that accelerated the work of sawmills and consequently required the invention of machines that would assist in tending the saws. Lumber moved so quickly through the new saws that it was no longer sensible for workmen to bring logs to the saw, turn logs on the saw, move timbers from one saw to another, and carry finished boards to the drying shed without the assistance of machines devised for those purposes. The demands of speed were particularly felt after the advent of the circular saw.

Although a British patent was awarded as early as 1777 and it was introduced into the United States in 1814, until the middle of the nineteenth century the circular saw was used principally for cutting veneer. At high speeds the centrifugal forces within a spinning blade and its expansion from heat while sawing could cause vibration and curvature of the blade. The need to mechanically flatten circular blades in their manufacture and during their use limited the hardness of the metal from which they could be made, and the use of soft metal led to a thicker blade and teeth that were quickly dulled.[12] Strains within the blades were somewhat relieved by providing radial slots toward the center of blades, and the effect of centrifugal pressures was reduced by tapering the thickness of blades (fig. 1.6). The greatest improvement of the circular saw resulted from inserting teeth of hard steel around the edges of a disc of softer steel. The maximum depth of cut for a circular saw was slightly less than half the blade's diameter, and increasing the diameter beyond certain limits would, of course, increase the saw's vibration and thus widen its





1.4 In the muley saw, variable lengths of the blade could be exposed between the adjustable muley heads. This ability to adapt the saw to the dimensions of logs resulted in a narrower kerf and consequent savings. (*Appleton's Cyclopedia*, 1880, 2:708.)

1.5 This gang saw of the 1880s includes a mechanism that moves the log forward at the same moment that the blades cut on their downward stroke. The bar below (*E*), which pulled the frame of blades down, was called the "pitman," an echo of the days of pit sawyers. (*Appleton's Cyclopedia*, 1880, 2:709.)

1.6 To avoid cupping of circular saw blades, slots could widen if the rim of the blades became hot and expanded or narrow if the center became hot. Inserted teeth were shaped of metal harder than that of the blade. The planer-tooth (above) was said to produce smooth-sided kerfs; the clipper-saw (below) was particularly suited for use on thin saw blades. (*Appleton's Cyclopedia*, 1880, 2:700.)

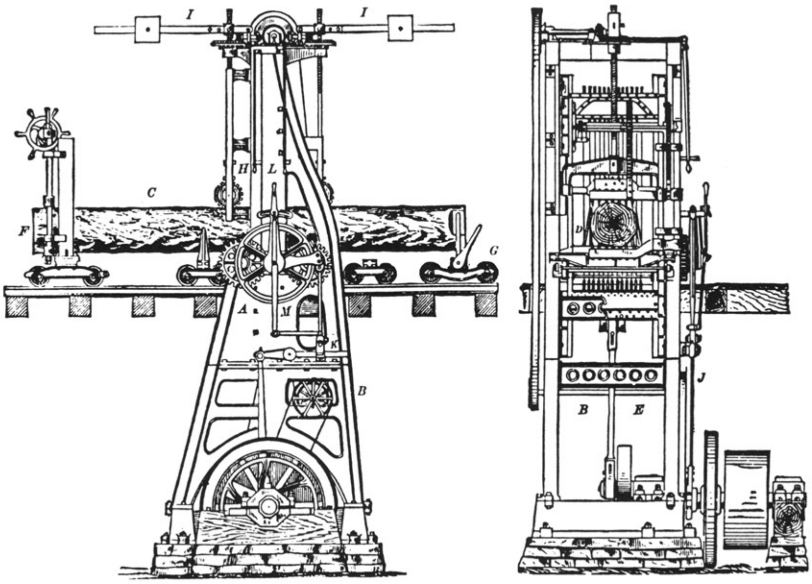
kerf. By the middle of the nineteenth century, the practical maximum diameter for a circular saw was usually considered to be around 5½ feet, which would saw a log little larger than 2½ feet in diameter. A solution to this problem was found by mounting a second and smaller circular blade above the first, increasing the total cut by about half this smaller saw's diameter (fig. 1.7). Whatever the difficulties inherent in the circular saw, it was fast. Other saws might average cutting as much as 5,000 feet daily (gang saws affording the pronounced advantage of their multiple blades), but in the 1850s circular saws could be expected to cut at least 1,000 feet per hour. Before many years had gone by that number quadrupled.[13]

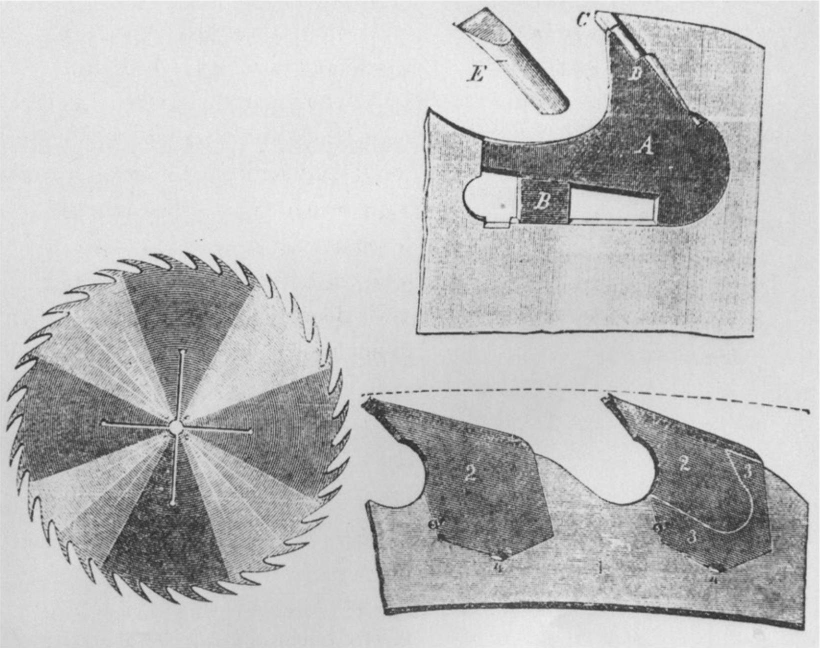
Circular and muley saws had kerfs of 5⁄16 of an inch at best, but usually cut a width of ⅜ of an inch, the same dimension as the kerf of vertical frame saws (fig. 1.8). A kerf of that width resulted in a loss of more than a third of the wood after a log was squared, the tree's taper was accounted for, and the remaining timber was sawed into boards one inch thick.[14] Vast piles of waste accumulated at mills with little possible use for them. Sawdust could be dumped into a stream, but it quickly accumulated and interfered with floating logs to mills downstream. A fraction of the sawdust might be sold for use in filling ice houses or as an agricultural fertilizer, and a small portion of the bark was needed by tanneries. Steam power for a sawmill could be produced with little cost by burning a sawmill's plentiful waste, trimmings, bark, and sawdust. In fact, fuel was so plentiful that in the 1890s mills in the northern parts of the United States instituted year-round operation, a result of the introduction of the "hot pond," the pool in which logs were kept being heated by a pipe carrying steam from the sawmill's boiler. Still, enough waste remained to cause a constant danger of fire, a risk always confronting lumbermen.

Although the band saw was invented and patented quite early in the nineteenth century, it was not useful until a blade could be manufactured that would run at high speeds without snapping. After the Civil War, the rising quality of metal and workmanship in the United States permitted manufacture of fine-toothed band saw blades of well-tempered metal. Blades as long as 60 feet and about 15 inches wide were looped over wheels above and below, and there was virtually no limit to the size of log that could be taken by a band saw. The narrow kerf of these blades produced, in most cases, less than half the amount of sawdust that came from other saws. Until the start of the twentieth century, much lumber was sawn at the start to the size at which it was to be used. Resawing, a method of shaping large timbers from a log and sawing them into boards and planks after shipping and as needed, was common by the end of World War I. For the second sawing, bandsaws mounted as multiple blades proved to be useful because of the accuracy and speed of their cut.[15]

It should be understood that at no time did one type of saw completely supplant the preceding types. At all times the larger share of sawmills were small plants, perhaps the wintertime occupation of a farm family. In such situations, investment in labor-saving equipment was seldom logical, for there was no serious shortage of man-hours for the work. Different species of trees and the probable uses for their wood often governed the choice of machinery. Only a few decades ago it was reported that the vertical frame saw (first to follow the pit-sawyer) was finding new favor in the United States and Canada, because it was well suited for sawing small and medium-sized logs.[16] One of the criteria for the planning of many mills was the simplicity with which the machinery might be dismantled when an area of forest land had been depleted and the time had come to relocate the saw at a place that offered a fresh stand of trees.

Machines for finishing lumber were a popular area of invention, so popular indeed that the case of the Woodworth planer, which combined feed rollers and cylindrical rotating cutters, became a *cause célèbre* of U.S. patent law. Woodworth's son in 1842 applied for an extension of his father's 1828 patent on the grounds that his father had been forced to sell off rights to the patent after workmen's protest demonstrations closed his initial display of the machine in New York (fig. 1.9). In 1836 a law had been enacted





1.7 A portable circular-saw mill, as manufactured in Cincinnati, used two blades to accommodate large logs. At the right is the carriage on which logs were moved through the blades. In the foreground, workers turn a log with peaveys, indispensable tools at lumber camps and sawmills. (*Appleton's Cyclopedia*, 1880, 2:703.)

1.8 At an exhibition in 1918, the West Coast Lumbermen's Association displayed a section of a fir log 4 feet in diameter, cut into lumber and reassembled. Note the similarity of this example to the methods of obtaining rectangular panes from a disc of crown glass (fig. 5.2). (*Scientific American Supplement*, 29 June 1918.)

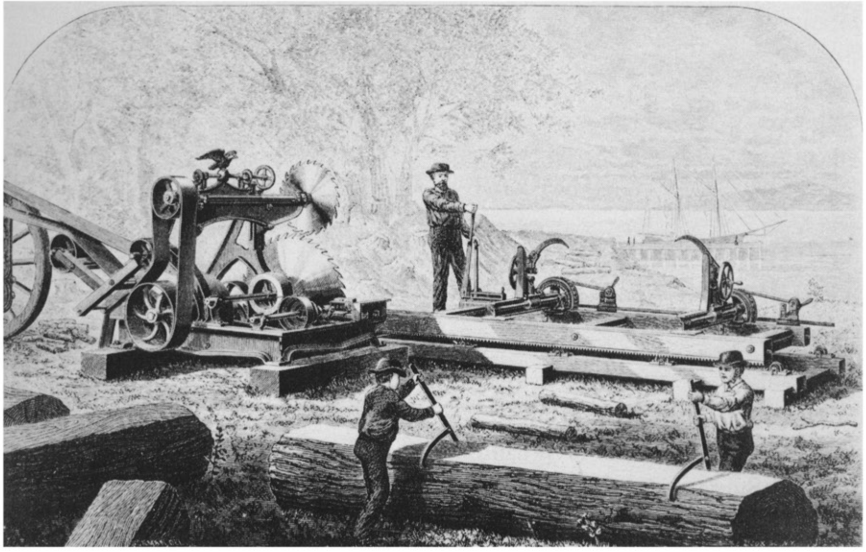
1.9 The Woodworth planer was capable of smoothing the upper and lower surfaces of boards with rotating cylinders, each having three blades. Edges of the boards could at the same time be smoothed or tooled with tongues and grooves. (*Asher and Adams Pictorial Album of American Industry*, 1876.)

permitting extensions of patents when the inventor "without neglect on his part [has] failed to obtain from the use and sale of his invention a reasonable remuneration for the time, ingenuity, and expense bestowed upon the same."[17] In legal action that followed Woodworth's application for an extension, his opponents questioned the legality of the extension, the validity of the initial patent, and ownership of the rights after an extension. A succession of courts, and eventually the U.S. Supreme Court, determined that upon issuance of an extension all rights reverted to the original patentee, excluding those who may have later purchased interests in the original patent. The Woodworth monopoly was based on restricted distribution of the machines and royalties charged on the amount of lumber planed, and it finally ended in 1865 after opponents presented to Congress a petition 50 feet long.[18]

* * *

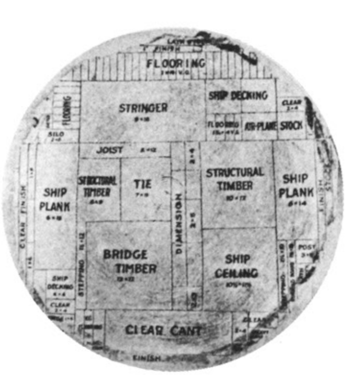
John Burroughs, the eminent American naturalist, in 1883 contrasted the "piny, woodsy flavor" of American poetry with the pastoral character of English poetry, which dwelt on fields and pastures and seldom spoke of woods.[19] But one should not conclude from this observation that the settlers of New England felt great affection for the forests that surrounded them and extended so far westward. As Theodore Roosevelt wrote, they viewed the land as "a region of sunless, tangled forests . . . with underbrush . . . dense and rank, between the boles of tall trees making a cover so thick that it nowhere gave a chance for the human eye to see even as far as a bow could carry."[20] To the pioneers, forests seemed threatening depths filled with insects, swamps, disease, and marauding redmen. Only by felling trees and clearing the land could space be created for agriculture, houses built, and income produced. Much of the colonial culture was grounded on the use of the region's wood. Barrels for Spanish wines and Barbadan sugar and molasses proved profitable, and New England pines, taller than those of northern Europe, provided masts that need not be weakened by being spliced. A small enterprise of shipbuilding began in New England and prospered. Yet no matter what commercial value could be found in the trees, they occupied land that was wanted for agriculture. For the most part, settlers moved west by wantonly clearing land, planting their crops among the gaunt, leafless trunks of trees that they had girdled and left to rot.

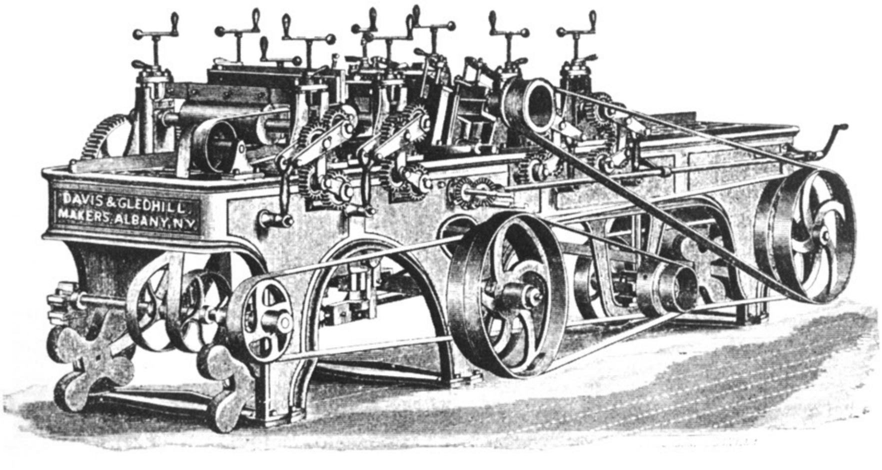
If the forests of North America proved to be a valuable resource, they also proved to be an exhaustible resource. By 1773 Rhode Island had cut all its available firewood and wood was bought from other colonies. A century later the woods of New York and New England had been so depleted that much of their logging activity moved westward to the forests surrounding the Great Lakes.[21] By the end of the shameful Black Hawk War, native peoples of the Lake area were confined to small reservations, rich farmland was made available to settlers, and dense timberland became available to loggers. In the 1850s hard times hit the eastern lumbermen and hastened their migration. Around 1860 the Lake area became the leading source of lumber in the United States. Chicago became the center of the U.S. timber trade, with lumberyards in 1856 already occupying 6 miles along the Chicago River and twice as much 15 years later. The South had a small antebellum timber industry,



largely coastal and marketing yellow pine and naval stores (turpentine, pitch, and rosin). During Reconstruction lumbering expanded, and after 1870 yellow pine from southern woods began to be seen in the North, even on the Chicago market. But when the timber available in the Lake region began to diminish in size, quality, and ease of access, lumbermen and loggers looked to the South and to the West, where vast stands of trees remained untouched.

The forests of Canada and the United States provided a rich source of timber for the westward expansion of those countries in the nineteenth century and a source of exports to Europe. By 1810 timber had replaced furs as the principal export of Canada, largely due to Napoleon's blockades that kept English ships away from Baltic ports. By 1890 the production of sawmills in the United States attained a value one-third greater than the output of all metallic production for that year.[22] In 1906 it was estimated that the lumber industry in the United States cut "approximately 40 million feet, board measure, of lumber, 11 billion shingles, 100 million railroad ties, 4 million poles, 20 million fence posts, 170 million cubic feet of round mining timbers, 3 million cords of pulpwood, 1½ million cords of tanbark, and about 100 million cords of firewood."[23] In the mid-nineteenth century, a succession of federal





laws—the principal ones including the Swamplands Act of 1850, the Morrill Act of 1862, the Timber Cutting Act and Timber and Stone Act of 1878—included provisions that were used by lumbermen seeking possession of forest lands.[24] The luxuriant stands of pine around the Great Lakes were dwindling and lumbermen of that area looked westward to fresh forests beyond the Rockies. After the California gold rush, some timber had been cut for local use on the West Coast and a few shipments were made to the Orient. When the Northern Pacific Railway Company in 1883 opened a route from Puget Sound to the Great Lakes, the timber of the northwest region suddenly became available. In the fashion of the business world of that time, there came to be timber barons who amassed vast stretches of woodland and operated both logging and milling phases of the business. Reformers, trust busters, and muckrakers loudly protested deforestation and predicted the depletion of the forests. Proponents described reforestation programs and the economic advantage to be gained from expansion of the timber industry. Since lumbermen made most of their profits from land and trees that were government property, this debate became repeatedly the subject of campaign promises and very seldom the topic of effective legislation.

A similar dichotomy is found in the descriptions of logging camps. By the latter part of the nineteenth century, logging camps had moved far from their owners' sawmills, for the machinery of a large sawmill handling large logs was no longer adapted to changing its location as loggers exhausted one mountainside of trees and moved on to another. Some journalists wrote heartwarming descriptions of robust lumberjacks filling the bunkhouses with jolly songs. Other descriptions pictured immigrant workers ill-fed, underpaid, and constantly endangered by the perils of their work.

Large trees had been felled for centuries with axes, because saw cuts became hopelessly clogged by rosin and sawdust. In the 1870s, West Coast choppers abandoned single-edged axes for a double-edged type. This new kind of axe allowed one edge to be used in trimming hard knots and other work that quickly dulled the axe's edge, and it saved the other edge for the work of undercutting, lessening the time required for sharpening the axe (fig. 1.10). It was the 1880s before saws with "raker teeth" were introduced. Typically, these saws bore groupings of about four cutting teeth with pairs of cleaning teeth between them, cut much shorter to pull sawdust from the cut. In addition, sawyers carried with them bottles of kerosene with which resin could be periodically cleaned from the saw blade.[25] The use of saws was said to double the number of trees that could be felled by a pair of lumberjacks, and an additional economy resulted from the fact that sawyers, needing much less skill than choppers, could be paid, according to Minnesota wage practices, little more than half the wage of choppers. In every logging camp, saw filers were charged with the responsibility of sharpening the saws, with due consideration of the length of a sawyer's stroke, the kind of trees being cut, and weather conditions. Power saws for this purpose were not introduced until the 1930s.

It is difficult to describe the way in which trees were cut and brought to a mill. Climate, terrain, the species being felled, the size of the lumbering enterprise, and even local traditions might determine the choice of procedures. Southern locations often were hampered by having to move heavy logs through muddy swampland; northern locations were more governed by seasons, cutting trees in the winter months and floating them to the sawmill when melting snow and spring rains made the rivers run high. A California redwood might offer particular problems, because its brittle wood could be shattered as the tree fell and a log 26 feet in diameter was invariably cumbersome and dangerous to move down even gentle slopes. Such factors could cause adjacent timber camps to use different methods, but at the same time similar methods might be employed by camps far apart in place and time.

For bringing logs from the forest to the sawmill or a waterway leading to the sawmill, the procedures varied according to the terrain. Logging began along the edges of rivers, where logs had to be moved only a short distance to the water. In flat, swampy woodland, such as the forests of the southeast United States, horses or oxen pulled logs along "corduroy" logging roads, surfaced by laying tree trunks across the route. On steeper slopes the "skidway" was often lined with logs to ease the handling, sprinkled in winter with water to make an icy coating and smeared with grease in warmer weather. In some mountainous locales flumes were erected, narrow triangular troughs holding a flow of spring water in which logs or sawn timbers would hurtle downhill for miles, one after another, and splash at the end into a river or lake. When engines were in common use, steam tractors pulled logs and portable "donkey engines" turned reels on which cables were wound to run derricks, hoists, and drag lines to move the logs. If logs that were destined for several sawmills floated in the same stream, they were marked, so that downstream each mill could identify and rescue the logs dispatched from its own logging camps.

On waterways used for other purposes, a more controlled method of moving logs was accomplished by assembling rafts. Units of logs were assembled in crisscross layers with 250 to 500 square feet of surface area. These cribs were linked together as rafts with overall dimensions as much as 135 feet by 160 feet, or even greater when they were assembled for travel down the Mississippi.[26] Workmen overseeing the drift downstream might assemble small huts on the rafts' top sides. On the St. Lawrence,

1.10 Standing on "springboards," fellers make a saw cut about one-third into the trunk and well above the hard grain and heavy sap of the base. Axes were used for undercutting before the workers turned their attention to the other side of the trunk, where the saw and iron wedges were used to fell the tree. By carefully sighting the direction in which the tree would fall, damage to it and other logs could be avoided. (*World's Work*, February 1904.)

1.11 On an Oregon river early in this century, logs float toward a cradle into which they will be loaded by a derrick. The cradle (foreground) is anchored along its back side to a row of pilings. After the cradle is filled and its logs are chained together, the frames on the near side of the cradle will be pulled away and the completed raft freed (background) for its trip to a mill in San Francisco. (*World's Work*, February 1904.)

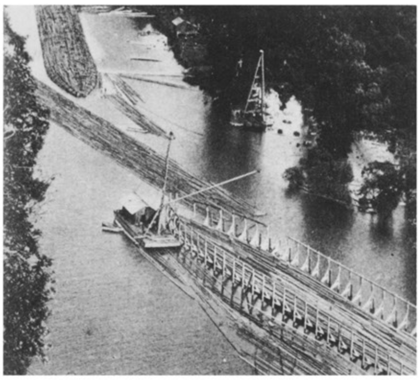
rafts were numerous and substantial, because the action of tides in the river slowed the journey to the sawmills. In the 1840s, Charles Dickens observed the many rafts of logs on the Saint Lawrence and wrote that their huts with flagstaffs erected beside them seemed "like a nautical street" floating downriver.[27] For transportation on the seas, workers assembled a "cradle" of wood, pointed and shaped like the hull of a broad-bottomed ship. In the fresh water at a river's mouth, where marine borers would not attack it, the cradle was half-filled with logs or trimmed timbers before a network of chains was fastened to hold its shape (fig. 1.11). When chaining was completed, the upper part of the raft curved to almost match its curvature below the water line. The cradle was then removed and the raft, which could be as long as 800 feet, as wide as 55 feet, and as deep as 35 feet, was ready to be towed across the Baltic Sea or southward along the coast of California.[28] Eighty to 100 tons of chains might be required to make a raft of average size sufficiently sound to be towed from the Columbia River of Oregon to a sawmill in San Diego.

* * *

The supply of timber has always been closely associated with the development of transportation. Although early demand for timber to be used in shipbuilding was undoubtedly less than that for fuel, both navies and merchant ships required the largest trees of the choice species, and their requirements pressed forcefully for the extension of timbering. During the seventeenth and eighteenth centuries the finest trees of England and her American colonies were hunted out and marked to indicate that they were reserved for the royal navy. It was nearly the end of the nineteenth century before shipbuilding had changed from wood to steel, and by that time the railroads had proved to be a hungrier market for timber. At first locomotives and railroad cars rolled on oak timbers with iron strips spiked on top. After iron rails came into use, they were secured to wooden crossties 6 by 8 inches in crosssection and spaced with 16 for each rail 30 feet long. This meant that the railroads' demand for wooden ties (their major, but not only, use of wood) was roughly the equivalent of providing a paving two inches thick and almost 9 feet wide along every one of the thousands of miles of railroad tracks, sidings, and spurs spread across the broad continent of North America. (European rail networks have been more inclined to use concrete crossties.) Since the average life of a railroad tie might be between eight and fifteen years, depending on the bed on which they rested, the amount of travel they supported, the wood from which the tie was cut, and the climate of the installation, there was a huge annual expenditure for the renewal of ties.

As the price of crossties increased, experiments were made in the application of preservative treatments that might extend their serviceable life, thereby reducing the annual cost of replacement. The situation worsened until in 1907 a railroad engineer grumbled, "It is no longer possible in the United States to purchase 80,000,000 first class cross ties per year." Some of the first railroad companies to investigate the use of preservatives were those that crossed the broad prairies of the western United States, far from forests and therefore burdened with higher prices for ties. Salt had been used in ancient times as a preservative for ship timbers, and wood for buildings was sometimes charred to prevent rot. In the middle of the seventeenth century the German chemist Johann Glauber developed a system by which timbers were charred, coated with tar, and then soaked in an acid resulting from the destructive distillation of wood. In the 1830s many more preservative treatments were developed involving such substances as a "decoction of tobacco leaves" and a "solution of India rubber."[29] Those preservative methods that continued in application included methods of immersion and pressure treatment using copper sulphate, mercuric chloride, and zinc chlorides, processes commonly marketed under their inventors' names (such as Boucherizing, Kyanizing, and Burnettizing).[30]

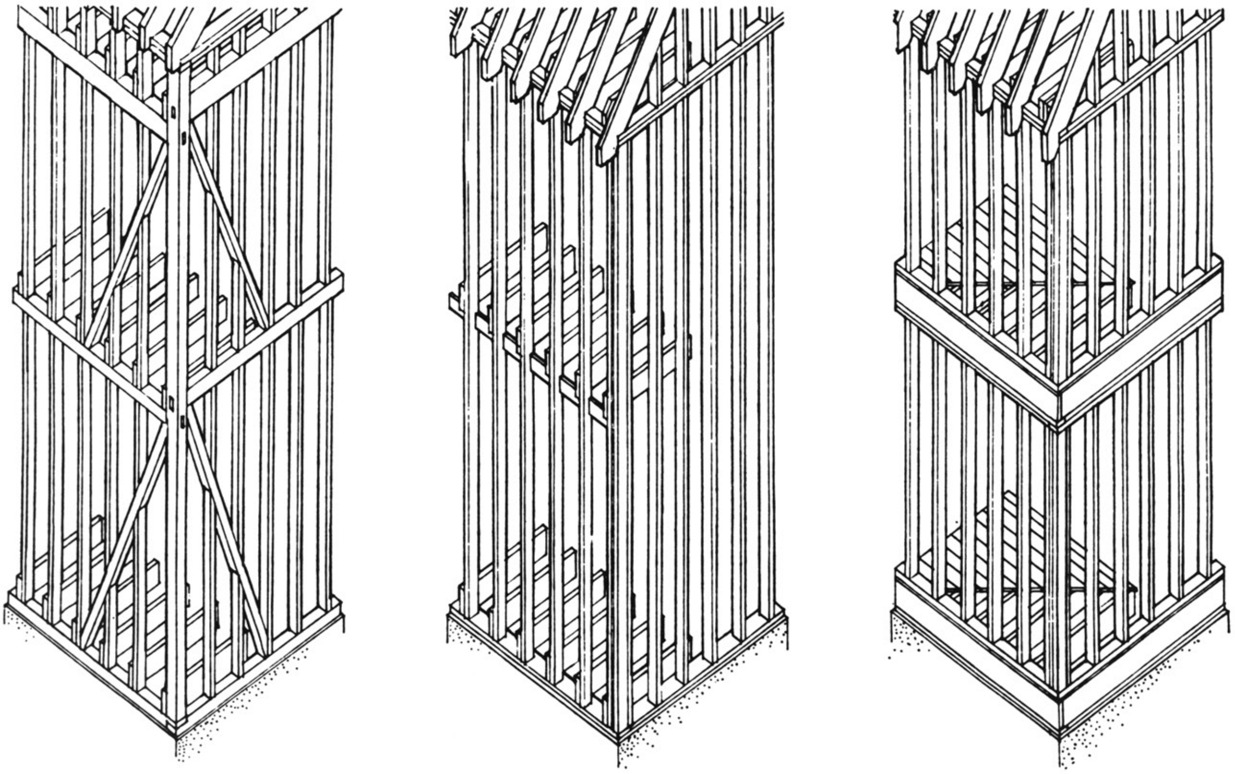
In the same period a method was patented in Britain for treating wood by pressure with the "dead oil of tar," which was also known as creosote. The carbonizing of coal produced a tar that could compete with Stockholm tar, long imported for caulking ships, and a variety of oils, those heavier than water being designated as creosote. Although some plants were established for the sole purpose of producing coal tar and coal tar oils, the introduction of gas lighting resulted in firms that were interested primarily in utilizing the gases that came from carbonizing coal and anxious to be rid of the odorous by-products.[31] Creosote was one of the first of an extraordinary array of products developed from coal tar as the chemical industries grew in scope and scientific knowledge. In the United States, railroad companies tested both creosote and metallic salts during the 1870s and found creosote most effective for use in coastal areas where marine borers were a problem and metallic salts suited for application in inland areas.[32] Any loss to the timber industry from the decrease of the demand for railroad ties was certainly offset by the market for pulpwood in the late nineteenth century, when it became a principal raw material for the manufacture of paper.



Traditionally lumber had been seasoned at the sawmill by stacking it in open stacks or under cover, but seasoning wood became more important with the advent of steam-heated buildings and their desert-dry interiors. Kiln drying was attempted around the middle of the nineteenth century, but it was a few decades before a workable system was found. In localities with high humidity and much rainfall, the traditional drying process meant that the sawmills' owners had to maintain a large investment in stored lumber and a rush of orders often could not be filled quickly. Even more influential was the reduction of shipping costs, for drying in a kiln reduced the weight of a carload of lumber by at least one-third. The typical early kiln in Minnesota was described as having steam pipes in a steel chamber, from which hot air was blown into any of several brick structures, each holding about 40,000 board feet of lumber. Air-drying lumber had been inexpensive, but sawdust and trimmings could provide the fuel for drying. The cost of building a kiln was soon paid for by savings in shipping costs, and lumber could be prepared quickly in response to orders and price fluctuations.

In 1832 George Washington Snow introduced to Chicago a method of framing buildings that used light pieces of lumber, usually not exceeding two inches in the smaller dimension, and relying more on nails than the traditional mortise-and-tenon connections. With the introduction of Jacob Perkins's nail machine in 1795, the price of a pound of nails had dropped from 25 cents to 8 cents by 1828 and would be 3 cents by 1842.[33] Balloon framing, so named because of its lightness, tolerated inexperienced carpenters and could be assembled quickly (fig. 1.12). It was, all in all, well suited for the buildings that settlers needed as they moved west. Balloon framing had been developed sufficiently by the 1880s to rely only on nails, without mortises. At the end of the century it was the predominant system of wood construction in the United States, and so it remained until it was succeeded by the western or platform system of framing, in which shorter members were employed.

As lumbermen found forests farther west in the United States, the distance from the sawmill to the consumer of lumber grew, and it became increasingly necessary to have recognized standards by which the quality of lumber could be described to the buyer and the needs of consumers could be communicated to the supplier. Sweden in 1764 had instituted a grading system that recognized four grades of commercial lumber, and seventy years later four similar grades were adopted in Maine. In 1873 the Lumbermen's Exchange in Chicago established grading standards (again using four levels: clear, select, common, and culls), but many regions or individual mills followed their own systems. It was difficult to enforce



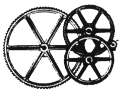
1.12 From left to right in the order of their development and use: braced or eastern framing, balloon framing, and platform or western framing. The simplification of carpentry was a principal factor in this progression. (Drawing by author.)

uniformity among the various lumbermen's associations, especially when the Panic of 1873, which for several years lowered the demand for lumber, was followed by clear signs of depletion in the pine forests of Michigan.

Grading standards were a major subject of debate when the first meeting of the Mississippi Valley Lumbermen's Association was held in 1891. In spite of the organization's name, it represented the northern white pine interests; few of its officers were not from Minnesota or Wisconsin and the most southerly director was from Hannibal, Missouri. Agreement on grading, of course, made it simpler to compare prices and, like many manufacturer's organizations of that period, the Association circulated recommended price lists to its members. As a member of the Northwestern Stave and Heading Association explained, "We are not getting up a trust or anything of the sort. We simply wish to establish uniformity of prices."[34] A year before the founding of the Mississippi Valley Lumbermen's Association, Congress had passed the Sherman Antitrust Act, destined to be more used against labor than against trusts, and one year after it was founded the Association was tried for violation of that law. In one of the first blows to the effectiveness of the Sherman Act, the judge ruled: "An agreement between a number of dealers and manufacturers to raise prices, unless they practically controlled the entire commodity, cannot operate as a restraint to trade, nor does it tend to injuriously affect the public."[35]

Timber companies had long been criticized for the manner in which they had taken advantage of legislation regarding federal lands. The wealth of open land had been openly used as a currency with which the U.S. government could forward certain policies. Grants of land rewarded war veterans, encouraged a westward movement of settlers, attracted immigrants, promoted the drainage of swampland, subsidized the extension of railroads, and financed the foundation of state colleges. Each of these laudable purposes seemed in some way to involve loopholes by which lumber barons were able to gain possession of vast areas of wooded land at extremely low cost. Men were paid to sign up for their 160 acres of wooded land under homestead laws, and then turned their claims over to lumber companies. A law of 1897 permitted landholders to donate their acreage to a protected area of wooded land and receive an equal acreage in another location. Under this program lumbermen traded the land they had already denuded for fresh timberland, and the Northern Pacific Railroad swapped over half a million acres of the least desirable land it had been granted when building the railroad across the northwest (only a fraction of the total amount of land they had received) in return for prime stands of timber in Oregon, Idaho, and Washington.[36]

Allegations and occasional convictions on charges of land grabbing and price fixing were not all that plagued the lumber interests. The IWW (Industrial Workers of the World), formed in 1905, a few years later concentrated its efforts on unionizing lumber workers, one of the few groups in which the IWW had a degree of success. Lumber companies resisted organization of their workers, a conflict that produced bloodshed and years of bitterness that are recorded in labor annals.



Veneers were used, as long ago as ancient Egypt, to apply the color and

1.13 This diagrammatic drawing indicates the relative position of the veneer knife (at left) and pressure bar. One of the spur knives (*A*), which cut the veneer to an exact length, is shown in position on the top of the log. A similar device, replacing the knife with a crayon, could mark the tight-cut side of the veneer, an important consideration when the veneer was assembled into plywood sheets. (A. D. Wood and T. G. Linn, *Plywoods*, 1943.)

pattern of rare woods to furnishings of simpler stuffs. The simplest method of preparing veneer was sawing a thin layer, which could be glued over a wood that was more practical because of its strength, price, or workability. The wide kerfs of early saws meant that much was wasted, but a larger area of precious wood could be shown as veneer than if it were used for the full thickness of the work. By 1805 a circular saw was being used in England for cutting veneer, and later developments produced the segment saw, fine-toothed segments of thin steel being held around the rim of a large center casting. The whole saw was usually at least ten feet in diameter, but it cut only near the rim, where the thin blades were exposed.[37] While they produced veneer about one millimeter thick, segment saws could not provide flitches of veneer that were significantly larger than usual. The veneer slicer, introduced in France around 1830, did little to increase the size of flitches, but by shaving off layers of wood it saved the amount that saws wasted as sawdust. Although a rotary veneer lathe, a machine that rotated a log so that a blade might cut off a continuous band of wood (as paper comes off a roll), was patented in the United States as early as 1840, it was about 1870 before a practical version was in operation (fig. 1.13).

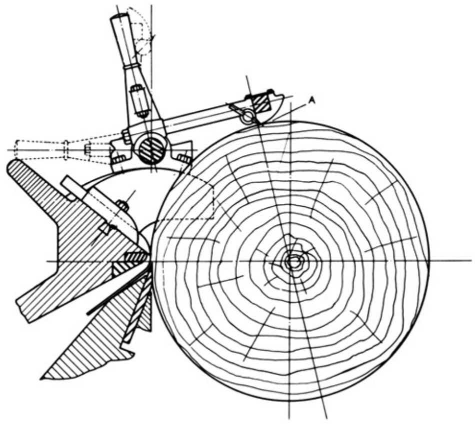
Veneer panels, glued with the grain of layers crisscrossed, were in use long before the term "plywood" originated around World War I. The English furniture maker Thomas Sheraton used such panels in his designs, and maple plywood was used for the wrest blocks of pianos (the piece holding metal pins by which piano strings are tuned). By the middle of the nineteenth century Steinway and Sons had begun using laminated sawn veneers for the curved sides of its pianos, and several manufacturers provided their sewing machines with cases having curved plywood surfaces.[38] Development of the rotary lathe permitted larger sheets of veneer, and in 1884 a factory in Reval (Tallinn), Estonia, started producing three-ply birch seats for bentwood chairs. At the turn of the century, plywood was a frequent material in the mass production of furniture. Estonian and Latvian manufacturers provided Great Britain with the plywood for furniture and for the chests in which tea and rubber were shipped from the Orient.[39] In the United States, factories around the Great Lakes produced plywood for furniture and sliced splints for making fruit baskets.

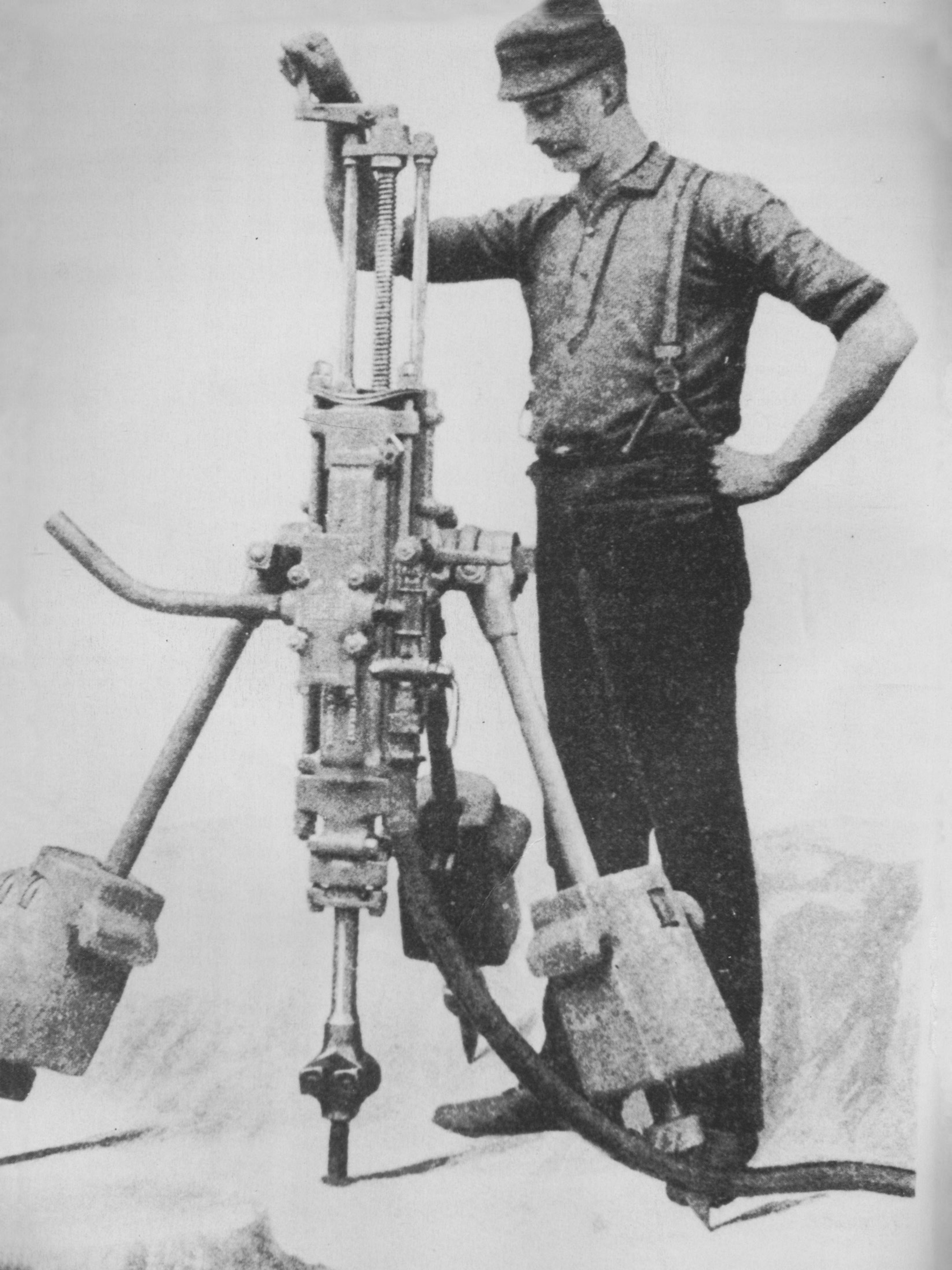
At the 1905 Lewis and Clark Expedition Centennial in Portland, Oregon, one firm displayed softwood plywood, less costly than the hardwood veneers used for furniture and suitable for structural purposes. The first uses for their product were door panels and the bottoms of cabinet drawers, and most plywood mills in the Northwest were linked to companies manufacturing doors and window sashes. By the 1920s an important market had been found in providing the material for automobile running boards and floor boards. However, because the glues used at that time were not sufficiently water-resistant, plywood was replaced by sheet metal in automobile production, and the exterior application of the material in building construction was limited.

Hide glue, an ancient substance made from the skins and bones of animals, was the first adhesive used to glue veneers, but 1912 saw the introduction of blood albumin glue, which, when applied with steam-heated presses, afforded a more water-resistant bonding material. By World War I, casein glue, made from milk curd, was the dominant type, and it was succeeded in the 1930s by soya bean glue, which was lower in price. In efforts to control costs, simplify manufacturing processes, and approach waterproof qualities, mixtures of such glues were devised to balance their individual characteristics. German companies in 1933 began manufacturing synthetic resin glues, a type that had been proposed in 1912 by Leo Hendrik Baekland, inventor of the first completely synthetic material, Bakelite. These phenolformaldehyde resins could be applied to veneer as a spray or a film. Their maximum waterproof qualities were obtainable with heat, and this discovery quickly revived the hot-pressing techniques that had been employed with blood albumin glues.

A drawback in the structural utilization of wood had always been the linear limitations of its strength. In the direction of its fibers, wood is a relatively powerful material, both supple and malleable. In other ways wood is weak, tending to split and shear easily. As linear structural members, timbers performed well, but at connections the more complex forces were limited by the lateral weakness of the material. By gluing crossed layers of veneer, plywood balanced these capabilities of wood, so long as it was used as a sheet. Laminated wood, a similar gluing of boards parallel, overcame the increasing restriction of available lengths and sizes, but the directional imbalance of strength remained.

The introduction of plywood suitable for use in building construction heralded a new era in the use of lumber. With advances in the chemistry of adhesives it was possible to reconstitute wood fibers, utilizing waste and eliminating many of the structural disadvantages of the linear anatomy of wood as it came from the tree. Chemical treatment of lumber under pressure could alter some of the natural characteristics of wood, enhancing its durability. Most important, steps toward reforestation were initiated. With varying degrees of urgency and success, the lumber industry began a transformation from being an exploitation of natural resources into what may become in essence an agricultural enterprise.





Technics and Architecture

The Development of Materials and Systems for Building

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Masonry

1689	Blasting employed in English mines
1786	Clay pots used in roof construction of the Théâtre du Palais Royal, Paris
c. 1800	Plugs and feathers used in quarrying
1835	Introduction of brick machines that extrude shafts of clay to be cut by wires
1845	Steam-heated tunnel brick dryers developed
c. 1850	Initial uses of the tunnel brick kiln
1850–80	Popularity of dry-press brick
1851	Model cottage, using hollow brick, exhibited at the Great Exhibition, London
1854	Invention of the wire saw for stone
1858	Introduction of the Hoffman continuous brick kiln
1860s	Power drills used in quarrying
	Channeling machine introduced in the U.S.
1871	Terra-cotta floor units patented (U.S.) by Balthasar Kreischer and George H. Johnson
1880s	Development of the Knox system of blasting in quarries

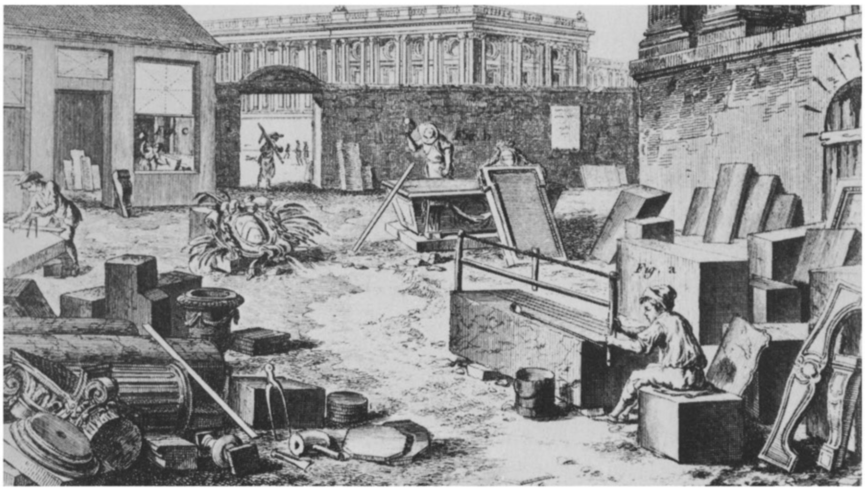
2.1 In an eighteenth-century stoneworker's establishment, a boy saws slabs from a block of marble. The bucket and ladle were used to pour a mixture of sand and water into the cut. (Diderot, *Encyclopédie*, 1762–1777, "Marbrerie," plate 1.)

The work of masons ranges from lowly sun-dried brick to the most richly veined marble, and the choice among masonry materials has always been largely a matter of cost. Proximity of a certain stone or the absence of stone in a region may, through cost differences, determine the dominant masonry material for each class of building there, may indeed establish a traditional scale by which the relative cost of a building—even the worth of its owner—can be estimated with uncanny accuracy. The presence of clay deposits and a thriving pottery industry may encourage construction in brick. Because the mason's materials are heavy and expensive to transport, in the past there was strong identification of a region's architecture with the local forms of masonry. Even the wall materials associated with periodic and local architectural fashions are most often attuned to financial considerations. When the emperor Augustus boasted that he had found Rome a city of sun-dried brick and left it a city of marble (which was a gross exaggeration), he was remarking only about one aspect of a program of governmental expenditure that set aside budgets for both public spectacles and the restoration of dilapidated temples. On the other hand, when a contemporary rhyme spoke of John Nash's finding early nineteenth-century London "all brick" and leaving it "all plaster," the verse merely recorded the fact that for the pretensions of speculative real estate one could cover brick with stucco and score it to resemble expensive and fashionable stones that had to be shipped there from other parts of England. Transportation costs were always an important factor in the price of masonry. The walls of a crofter's cottage might be made by its owner from rubble picked up in nearby fields, but an emperor's tomb would be carved by skilled artisans from fine stones brought from far away. In thirteenth-century England the charges for carting stone from a quarry near Bath to a building site about fifty miles away were seven times the cost of the stone itself.[1] At the same time, some French stones, which could be brought to England by water, were less expensive than English stone that had to be hauled across land. Often the use of brick and stone as ballast for wooden ships reduced their prices significantly.

Although both of the major categories of masonry materials, stone and brick, were primarily produced by relatively small local enterprises, we must remember an essential difference. Brickmakers seldom made anything but brick. Whether their brick was meant for construction or paving, they were not often also engaged in firing pottery. In contrast, quarries had vast amounts of waste and the stone shipped out for use in buildings and engineering constructions might be as little as 10 percent of the material quarried. Mammoth piles of waste stone could be left, cut into paving blocks, crushed for gravel, or ground to be sand for glassmaking—the choice among such options being determined by the characteristics of the stone and the market for it.

* * *

All quarrying methods must vary according to the hardness and internal structure of the stone being extracted, the terrain from which it is to be taken, and the materials available for tools. In ancient times the procedure in almost all cases began with hammering out trenches along the sides of the block that was to be removed, iso-

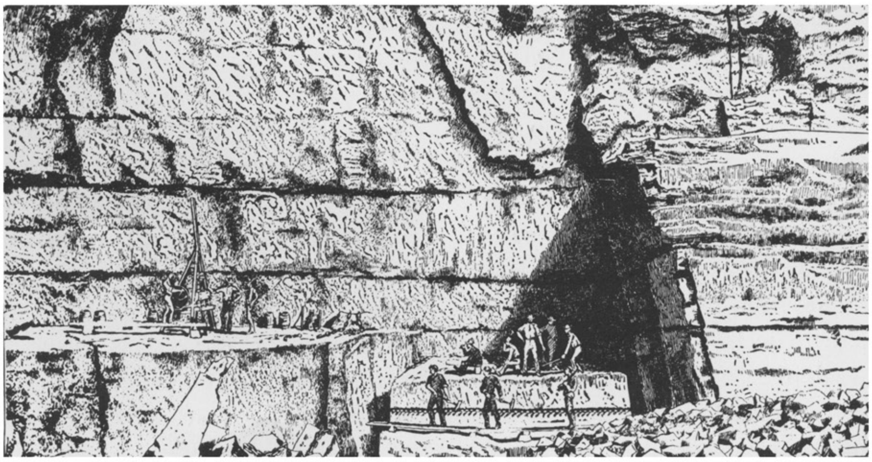


lating the block from the stone around it and exposing the sides of the blocks that were to be removed next. Trenching was accomplished by crushing the stone with rocks that were harder, chipping it out with iron picks, or making a series of holes with a drill point and breaking out the material between them.[2] After the desired depth had been reached by trenching, the exposed edge of the bottom face of the block was undercut or split by drilling a series of shallow grooves in which wooden wedges were placed or metal wedges were hammered. When wooden wedges were used, they were soaked with water until expansion of the wood split the block from its position. For soft stones, saws might be employed to speed parts of this work. Where large quantities of stone occurred with few flaws, these procedures could be used to form a series of steps up a vertical face of the quarry. Each block, once it had been detached from the surrounding stone, could then be moved forward on the top of the next step and lowered step by step to the bottom of the quarry.[3] The methods described here continued to be used with few significant changes until the eighteenth century. If trenches were to be deep enough to isolate large blocks of stone, they had to be made wide enough for a quarryman to work in them. Toothless metal saws, their cut fed with water and fine gritty sand, could be employed on some stones, but sawing was so laborious that it was commonly used only for slicing blocks after they had been removed from the quarry (fig. 2.1).

The mainstay of later quarrying methods was the jumper, which remained in use in the United States through the end of the nineteenth century for drilling deep holes in certain limestones.[4] The jumper was an iron rod usually 5 to 6 feet tall with steel points at both ends. At mid-height the rod was enlarged in diameter to increase the jumper's weight, which in most cases totaled around 20 or 25 pounds.[5] Placing one hand high on the rod and the other low, a quarryman lifted the jumper and drove it down on the stone. It is recorded that at an English granite quarry a demonstration showed 112 blows of the jumper formed a hole 2¼ inches deep. Echoing off the hard walls of quarries, the clang of jumpers was long a symbol of quarrying.

The alternative to the jumper was a hand-borer team of three quarrymen. One of them knelt and held upright a sharp-edged rod, while the other two alternately struck blows with heavy sledge hammers. Between blows the rod was turned in the hole. There was debate about the relative merits of the jumper and the hand borer. In the 1890s the jumper was strongly favored by many European and Australian quarrymen, but in the United States hand-drilling was generally preferred. Where deep holes were required, it was recommended by many that the first several feet be drilled with a hand-borer and the work completed with a jumper. It was contended that as the hand drill became longer it less effectively transmitted the force of the hammers' blows to the stone at the bottom of the hole, and that when the hole became deeper a jumper of greater length and weight could better be used.[6]

If possible, quarries were established alongside water, so that they might take advantage of water transportation. An escarpment beside water offered the further advantage of presenting its layers of stone for inspection so that the quality and consistency of the stone could be ascertained. While a distant and elevated locale might be a source of unusually fine stone, such a quarry was often abandoned in favor of a river valley cliff of somewhat less desirable stone.[7] Earth and debris above the stone was relatively unimportant if building stone were to be quarried, for the blocks would be trimmed and cleaned before they left the quarry; however, stripping the top was critical for later quarries that produced stone for industrial purposes (as sand for glass-making or flux for smelting) or for use as crushed stone for concrete. The manner in which building stone was to be extracted was largely determined by the seams that were present. Horizontal seams, arising from the manner in which the material had been originally deposited, may be spaced apart only a few inches or a hundred feet, as with some limestone deposits in Indiana. Where convenient, these seams were used as limits of block size, simplifying extraction. Otherwise, horizontal drilling was necessary to free the bottom face of a block (fig. 2.2). Vertical seams, caused by compressive forces acting within the

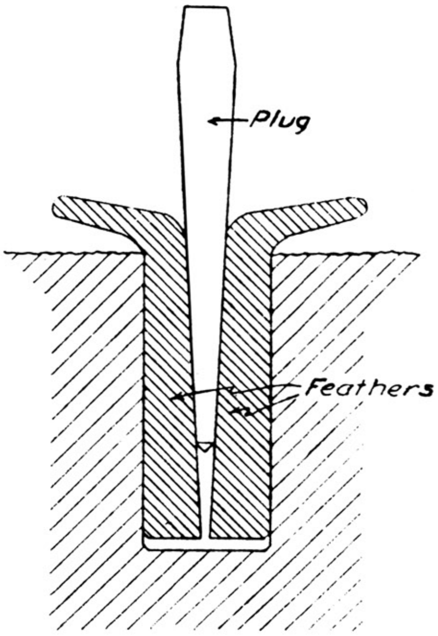


2.2 In a Connecticut quarry, workmen split out a block of sandstone. Large iron wedges are placed in a groove cut 4 to 8 inches deep, and workers walk along to hammer each wedge in turn, evening the pressure on the stone. (G. P. Merrill, *Stones for Building and Decorating*, 1903.)

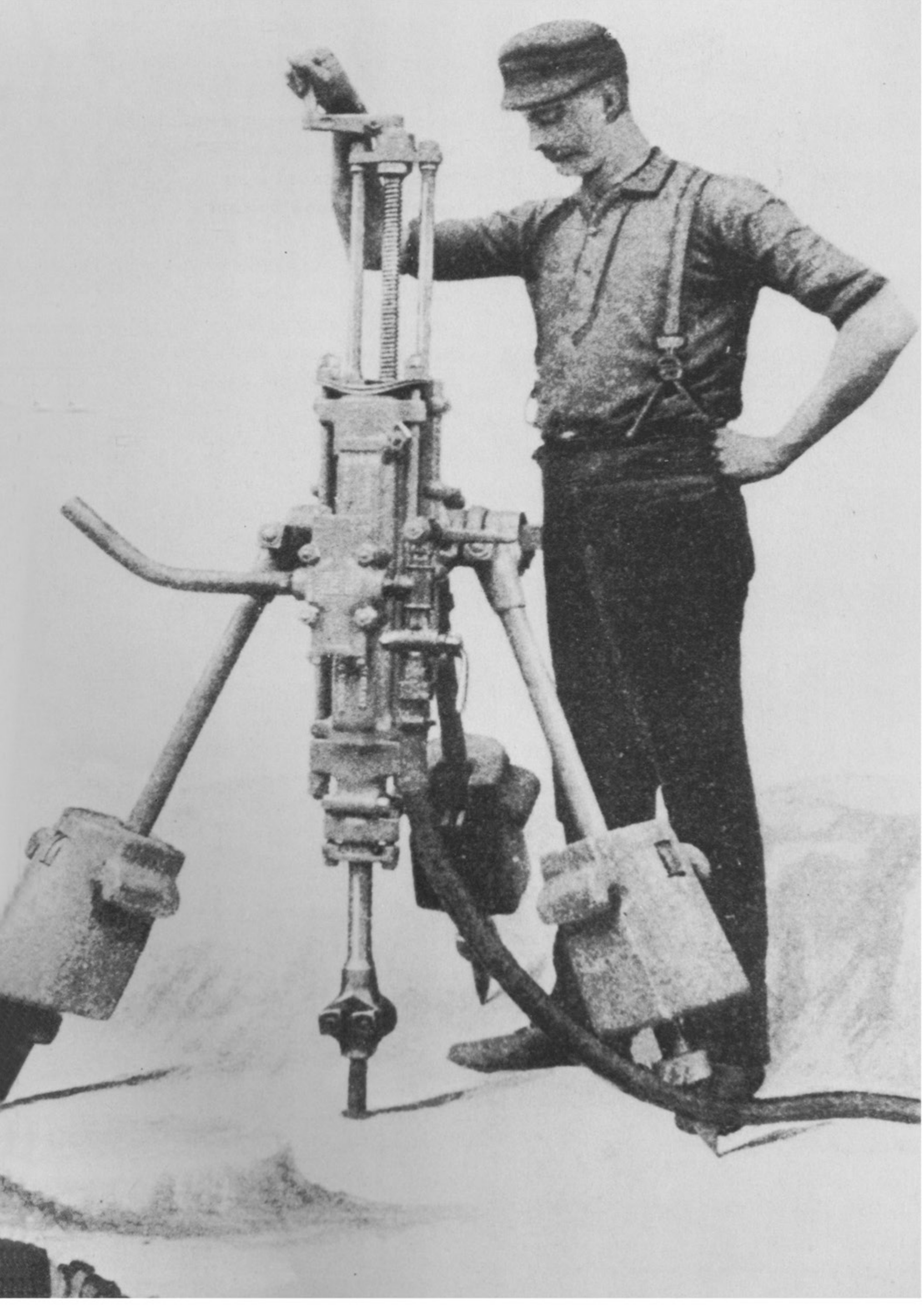
2.3 Even after the use of blasting powder had become customary for splitting out large blocks of stone, dividing the block into smaller pieces was done with plugs and feathers. The steel feathers were half-rounds at the ends that filled the drilled hole and thus evenly distributed pressure as the iron plug was driven in deeper. (G. A. Thiel and C. E. Dutton, *Architectural, Structural and Monumental Stones of Minnesota*, 1935.)

stone, usually occur in two systems of parallels in directions that intersect at right angles. In some quarries these vertical seams may be spaced as much as 30 or 40 feet apart.

Grooves and wedges to split off blocks of stone were replaced around the beginning of the nineteenth century by the use of "plugs and feathers." Holes made with jumpers or hand-borers (later pneumatic drills) were spaced about 6 inches apart, and in them were inserted plugs, which were tapered wedges of iron, driven between two iron feathers (fig. 2.3). Since the feathers were flat on one side to hold the plugs and curved on the other to fit against the sides of holes, they assured that pressure would be evenly applied against the stone around the hole. An English granite quarry drilled holes 3 feet deep, but in the 1930s a Minnesota granite quarry found that a pattern combining holes that were 6, 18, and 36 inches deep gave a straight and even break through a ledge about 13 feet thick.[8] Another account tells of splitting rock to a depth of 25 feet if the plugs were hammered in at the end of the day and left overnight.[9] Whether the system employed was grooves and wedges or plugs and feathers, such methods eliminated the immense waste of material and expenditure of labor that was involved in trenching around blocks in order to remove them from the quarry face.



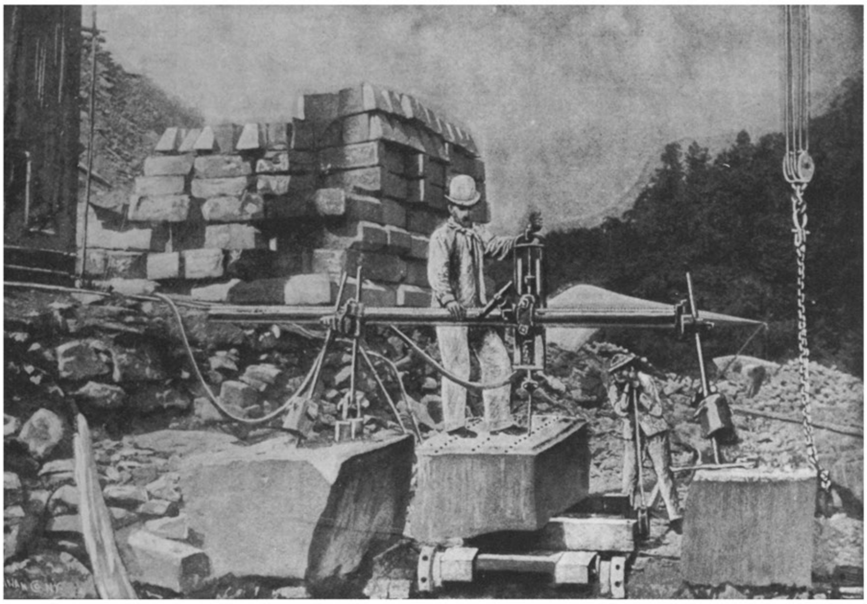
By the 1860s, power drills much like those used in mining were available, both steam-powered and pneumatic (fig. 2.4). Pneumatic drills had the advantage of providing jets of air that emptied the hole of accumulated waste that would reduce the efficiency of a drill, and they were also air-cooled, which eliminated the need of periodically pausing to avoid overheating the drill. One estimate reported that in working granite a power drill and a single operator could in one day accomplish ten times as much work as a team of three hand-borers.[10] Although many small quarries delayed acquiring power-drilling equipment because of its cost, the conversion was inevitable because boring holes was one of the most costly aspects of quarrying. Most power drills were mounted on heavily weighted tripods, but bar drills were mounted on a horizontal steel rod so that they could be quickly repositioned when a line of holes was to be bored (fig. 2.5). The methods used to extract blocks necessarily varied according to the type of stone being quarried, the layout of the quarry, and the purpose for which the blocks were intended. However, a typical quarry would employ wedges or plugs, hand borers, and power drills at the same time.

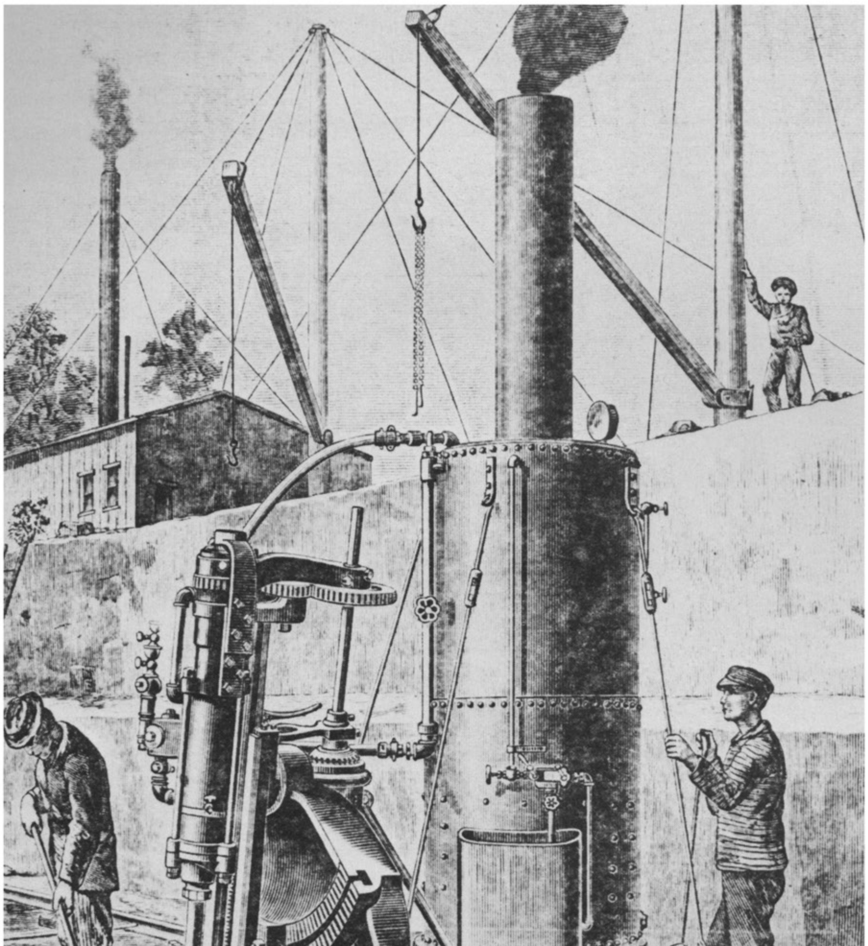


A steam boiler, mounted on a wheeled frame that rolled along tracks, provided power for the first type of channeling machine, which was introduced in the United States in the 1860s (fig. 2.6). The boiler was connected to a piston that drove a set of sharp-pointed vertically mounted steel blades. As the channeler moved along its tracks, the blades chipped away a channel slightly more than 2 inches wide. As the cut deepened, the blades were lowered, and at certain depths they would be replaced by longer sets of blades. In limestone the channel might be 10 to 12 feet deep and the cut could extend as far as 100 feet across the floor of the quarry. When the cut was to be deep and long, two or more channeling machines could work on a track at the same time, and duplex channelers cut on both sides of the track, usually spacing the cuts about 8 feet apart.

Channeling machines were principally used with stones such as limestone, sandstone, and marble. In granite quarrying the term "channeling" meant, instead, boring closely spaced holes the full depth of the desired block and cutting out the material between. It was a laborious and expensive procedure, but it gave a straighter face than the usual methods of splitting and it avoided shattering the stone, which was always a risk of blasting.

Handguns and artillery were present in Europe by the end of the fifteenth century, the explosive power of gunpowder having been enhanced early in the century by the development of granulated powder. At some time in the seventeenth century gunpowder began to be used for blasting in European mines, and by 1689 it was regularly used in some Cornish mines.[11] Miners drilled deep holes, 3 to 4 feet deep, and poured black powder into them, filling the holes the rest

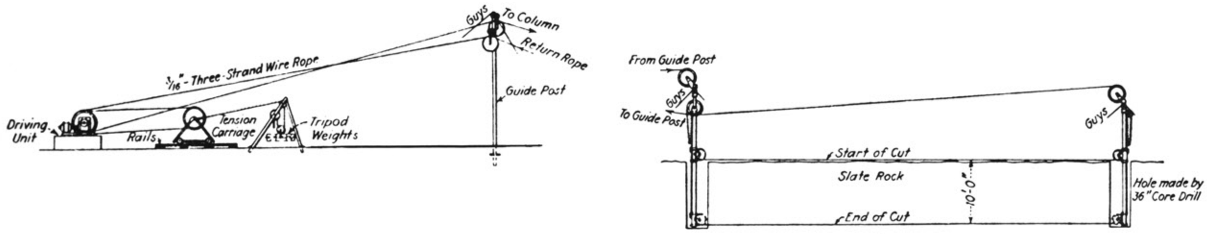




2.4 Steam-driven reciprocating rock drills of the 1890s were supported on heavily weighted tripods. A crank at the top was used to lower the piston and drill bit. Steam equipment was largely replaced by that employing compressed air, particularly in northern climates where steam cooled too much before reaching the drill. (*Appleton's Cyclopedia*, 1897, supplemental vol.)

2.5 A workman of the 1890s employs a pneumatic bar drill to split a block of granite in a Delaware quarry. Supported by weighted legs at the ends, the bar has a notched track along which the drill is moved. (*Cassier's Magazine*, November 1891.)

2.6 Channeling machines could operate on their own boiler, as shown here, or on steam supplied through a hose. Channelers were particularly useful in extracting a key block, the first to be taken from a fresh layer at the floor of a quarry. After channeling around a rectangle only about 2 feet wide, this small block could be broken off and lifted out, giving room to drive wedges at the bottom of larger blocks after they were channeled at their sides. (*Cassier's Magazine*, November 1891.)



2.7 At the driving end of a wire saw (left), a tripod weight of 800 to 2000 pounds maintained tension in the wire. At the cutting end (right), the portion of the wire in contact with the stone could be mechanically lowered. In slate quarries the cut could be as long as 100 feet and not more than one-quarter inch wide, the diameter of the cable. (O. Bowles, *Stone Industries*, 1939. Courtesy of McGraw-Hill.)

of the way with clay and leading fuses to the powder. The same methods were used for quarrying, but, unlike mining for ore in which a crumbled residue was desired, quarrymen extracting building stone hoped for a controlled split, avoiding damage to the block or adjacent portions of the ledge that was being worked. An account from the middle of the eighteenth century describes the procedure in quarrying:

> When a little hole is made [by the jumper], they put in water as they go on boring, they from time to time clean out the hole in the manner as people clean a gun barrel. . . .
>
> When the hole is thus made of the depth they chuse, they clean it very well out, and make it dry. They then put in a quantity of gunpowder, . . . sometimes not more than half a pound and sometimes two or three pounds. When the powder is in, they thrust down a small wire reaching down to it and up to the surface. They then make up some very stiff clay, or other such matter, and ram it into the hole extremely firm, filling it entirely, and in the strongest manner possible. When the clay or other matter is well in, they draw out the wire; this leaves a little hole quite down to the powder at the bottom. They then fill up this hole also with powder, and lay a train of gunpowder from this. At the end of the train they lay a piece of lighted touch-wood [punk], and leave it to take effect.
>
> It is their business to get away, for the effect is very violent. Several tons of stone are generally loosened by the blast, and frequently pieces of two or three pounds weight are thrown like cannon-shot to a considerable distance.[12]

A method for controlling the force of blasts originated at the sandstone quarries around Portland, Connecticut, principal source of the material used for the brownstones of New York. The beds of this stone were usually 10 to 20 feet deep and blocks were extracted by drilling holes from 10 to 12 inches in diameter. Canisters made of two curved pieces of sheet metal, the cross-section pointed like an American football, were placed in the holes. After the canisters were filled with powder, sand or earth was tamped around them. In granite, a cluster of two or three closely-spaced holes could be drilled, the walls between the holes broken out, and powder poured into that cavity. In both of these procedures the major force of the explosion would act on two opposite principal faces of the shape containing the powder, instead of acting equally in all directions as in a round hole. This caused cracks to form at the ends of the shapes.[13] The Knox system of blasting, introduced in the United States in the 1880s and still in use through the 1940s, drove a steel reamer down a completed drill hole, adding points on opposite sides of the hollow. Thus the hole itself assumed the form of the Portland canister.

The amount of powder to be used in blasting was a matter for judicious consideration, for a misjudgment might result in the wasteful shattering of stone or an irregular split that would greatly increase the labor required to shape the block. Skilled blasting not only separated the block from the surrounding stone, it moved it forward ready to be transferred for scabbling, the process of trimming it to a rectangular shape. At a Portland, Connecticut, sandstone quarry, a block 150 feet long, 20 feet deep, and 11 feet wide, weighing 3,300 tons, was split off and moved out 4 inches by setting off 2 pounds of powder in each of 17 holes; in an English granite quarry by firing 30 pounds of powder in a hole almost 16 feet deep a block weighing about 2,000 tons was moved out a foot.[14]

A later system of dividing stone, developed in Europe through the last half of the nineteenth century but only used in the United States after the 1920s, was the ingenious wire saw, which was useful both in quarrying and trimming limestone, marble, or slate (fig. 2.7). A twisted three-strand wire rope pressed down on the stone as a slurry of water and sand was fed into its cut. The loop of wire ran between two vertical standards, each holding two pulleys, the lower ones descending as the cut was made. Either the saw wire or a driving wire could extend to a steam engine or an electric motor. The standards might be guyed in place on the floor of the quarry or sunk into pits 10 to 14 feet deep and about a yard in diameter. It is reported that in quarrying slate a cut 80 feet long progressed at a rate of about 4 inches per hour. According to comparisons made in the 1930s, in addition to the advantage of its producing the least waste of any method, wire sawing cost about one-third as much as channeling.[15]

Once a large block of stone was detached from its place, it was necessary to subdivide it into workable pieces having dimensions nearer those at which it was to be used. For instance, in a limestone quarry, channels 4 feet apart and 8 to 10 feet deep might be 50 or 60 feet long, cutting out a long thin block. The entire block could be turned on its side by steam power, piles of broken stone being placed beneath to cushion the block's fall and prevent its being damaged.[16] Any of the methods available for extracting blocks (except channeling) might be utilized in subdividing them. Jumpers or pneumatic drills would make a line of holes in which plugs and feathers were driven to break the block into pieces of more manageable size. The extent to which stone was finished at the quarry depended largely on transportation, and in the case of limestone and sandstone, it was far easier and therefore less expensive to work the stone soon after it came from the quarry, before it had dried and hardened.

In Greek and Roman times it was the custom to trim stones at the quarry into a rough approximation of their eventual size, leaving an extra dimension to withstand the hazards of transportation. After the stone had been moved to the construction site, all the faces adjoining other stones were chiseled to their final surfaces, and the stone was set in place. Once the stones has been placed, exposed surfaces were leveled and finished. This procedure involved a trade-off between leaving the stone rough to protect against damage as it was brought to the site, usually a matter of yoked oxen pulling a sledge loaded with the stone, and reducing the weight of the stones that had to be hauled. (If 1½ inches were left on each face of a cube of limestone 4 feet on each edge, the weight would be increased by about one-sixth, almost a ton, and this would be one-third greater if the stone were newly quarried and had not dried.) The same methods were applied in medieval times, although a large part of the more decorative work might be completed at the quarry to conform to the dimensions, drawings, or templates provided by the architect.[17]

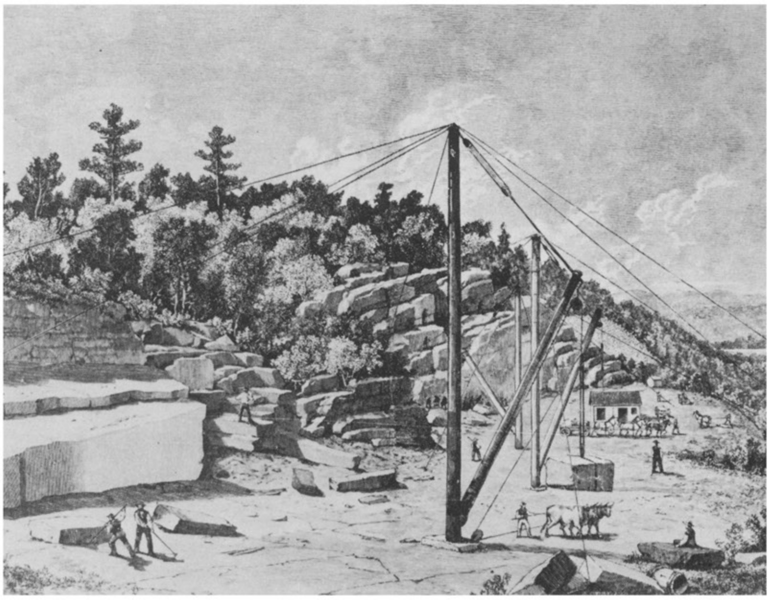
2.8 As in this New England granite quarry, stone was extracted in a setting of derricks, cables, and pulleys. The heavy block and the vertical distances within the quarry or leading to a riverbank barge led to the development of intricate systems, most of which were elaborations of the simple boom derrick shown here. (*Asher and Adams Pictorial Album of American Industry,* 1876.)

The least costly stone, of course, came from ruins of the past. Saxons built with stones from the remains of Roman buildings; early Christian and Byzantine builders used the material from classical ruins and even incorporated into their designs the ornament and architectural detail that had been previously carved. Should there be no ruins to quarry, a choice among the available stones was required. In most cases old buildings stood as evidence of the weathering qualities of the stones that were to be found in any region. Certain stones became standards of comparison, respected for the qualities that time had tested. Portland stone, which played a major role in rebuilding London after the Great Fire of 1666, had been used in the city since the fourteenth century, and was long acknowledged as a standard against which other stones might be judged. So long as wood was the fuel most commonly used for heating houses and manufacturing goods, the air of cities offered little threat to stonework. When forests became depleted and wood became costly, coal came to be the principal fuel, cities became crowded and sooty, and the foul air of urban life threatened even the soundest of stones. At the same time, rail transportation made it easier to select stone from quarries farther away without shipping costs interfering with the choice. But many of these stones had been insufficiently tested in the locale for which they were selected.

Caution was not always a sufficient safeguard when selecting stone. Four years after the burning of the Houses of Parliament, a commission was appointed in 1838 to choose the stone from which the new structure would be built. After excluding igneous stones from consideration because of the expense of working them, the commission reportedly visited more than a hundred quarries, inspected many public buildings, and ordered laboratory tests made. Reaching the conclusion that "in proportion as the stone employed in magnesian-limestone buildings is crystalline, so does it appear to have resisted the decomposing effects of the atmosphere," they chose a dolomite limestone from the area of Bolsover Moor in Derbyshire.[18] It was later found that this quarry could not provide stones large enough, and a second investigation led to the use of stone from another locale. Only 14 years after the project was completed, a committee was appointed to investigate "the decay of the stone of the New Palace of Westminster," and one of the problems to be considered was the effect of "the acids diffused in the London atmosphere."[19] Stone from the same quarry had been used for the Geological Museum, where it had not suffered significant damage.[20] Therefore, it has been assumed that the fault lay in the care with which stone was selected from the quarry—a constant problem because of the degree to which the quality of a quarry's stone might vary—and the fact that much of the work had been laid without due regard for the natural bed of the stone.[21] In the nineteenth century, methods for protecting stone were widely discussed. Painting required maintenance and blurred the carvings and ornament; oils and waxes also needed to be applied repeatedly; and neither of these methods fully protected against the damage that could be caused by moisture within a wall and the actions of frost.

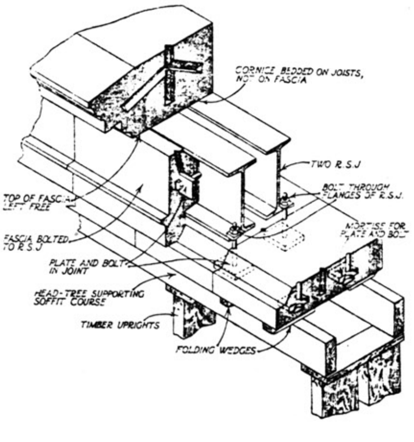
After the introduction of steam power in quarrying, there was an exploration of devices by which pieces of stone could be moved about. Many quarries simplified the task of moving stone to barges by building small railways, and, as in mines, light tracks were laid to make it easier for workmen to push heavy loads. Hoists and derricks assumed many tasks for which levers and windlasses had in the past been the only equipment. Because of their origins, granite quarries usually ran deeper than those from which limestone or marble were taken, and lifting equipment was particularly important for them (fig. 2.8). The overhead cableway was introduced in the 1870s and one type was called "Blondin" after a French tightrope artist who had several times crossed Niagara Falls.[22] With a Blondin and a steam-driven hoist, heavy blocks could be picked up and moved to another part of the quarry without the exertion and delay that had previously been required.

Roughly shaped blocks were taken to the mill, where they were worked to attain the exact dimensions shown in construction drawings and the textural finish specified for their visible surfaces. According to the types of stone, there was considerable variation in the tools and procedures used, but in general the methods followed those that can still be observed today in many parts of the world. An experienced workman trimmed the edges with a chisel, squaring the stone and setting its dimensions; the task of leveling the faces and applying the desired textural treatment was usually left to apprentices who chipped away with chisels, points, and hammers faced with sharp steel teeth. With pneumatic tools the procedure was much the same, only speed being gained by mechanization.

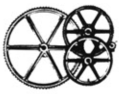


Machine finishing was usually done by circular saws or gang saws, parallel blades adjusted in their spacing according to the desired thickness of the slabs that were to be cut. The blades of gang saws for cutting stone had no teeth, and at the end of each stroke they lifted to allow a mixture of sand and water to flow into the cut. Circular saws were usually 5 feet or larger in diameter. The edges of the blade were notched to receive steel teeth, and, for granite, steel shot was used as an abrasive. For granite or limestone a gang saw would cut at a rate of about 6 inches per hour, cutting several slabs as it went; a circular saw cut at a rate from 3 to 16 inches per minute, but made only one cut.[23] In the late nineteenth century, other power tools for finishing, polishing, and grooving stone were introduced, most of them originating in the United States and transferred from there to European quarries. Pneumatically driven chisels and hammers, steam-powered polishers, planing machines, and lathes increased the speed with which the desired finishes could be achieved, although certain attractive traditional textures could not be reproduced by machine.

At the same time that the mechanical equipment of quarries and stone milling plants became plentiful, practical, and varied in function, the adoption of steel frame construction began to decrease the demand for building stone in the United States (fig. 2.9). Tall urban buildings, which formerly required ground-floor walls of extraordinary thickness, were built with thin walls supported on the steel beams of each floor. Quarrymen sadly recognized that their stone was no longer the very substance of buildings, but had instead become a surfacing material. This change occurred much later in European countries, where steel frame buildings came later into use. In many cases the declining use of building stone was offset by the growing use of crushed stone for reinforced concrete in engineering and building construction projects.



2.9 Using stone as a covering for steel frameworks meant that much less stone was employed than in bearing-wall construction. However, notching the back of the stones to within a few inches of the front surface was often more expensive than carving the details that would be visible. (*Building*, December 1927.)



2.10 Between 1815 and 1850 English production of brick more than doubled, although firms remained small and no significant technological advances were made during that period. Because suitable clay was not to be found everywhere, the expansion of brickmaking was largely due to the construction of canals that could economically bring coal to the kilns and carry off the fired brick. (Bettman/Hulton Archive.)

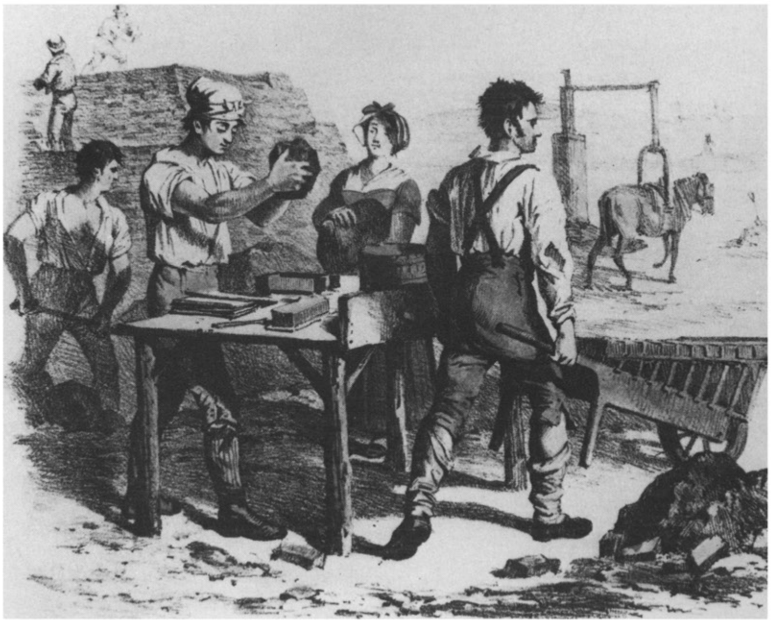
Fired bricks were seldom used in Greek or Roman buildings, mud bricks or sun-dried bricks being sufficient for the climate. Sun-dried bricks, laid with mud joints, were sturdy and avoided both the tedious work of quarrying stone and the cost of fuel to feed brick kilns. The exterior surface could be plastered to improve its appearance and offer protection from rain. Fired bricks were sometimes incorporated for additional strength at corners and at the jambs of doors. It was the final century of the Republic before wealthy Romans began to include marble in their houses, and only in the age of Augustus did the use of fired brick become significant.[24] Brick walls in Roman construction were combinations of masonry and concrete, with bricks laid at the outside surfaces and the space between filled with concrete poured over layers of rubble or brickbats.

Medieval architecture was dominated by brick in the areas of northern Europe that had little stone, a zone starting in Holland and crossing Germany to the lands around the Baltic Sea. In England, Flemish brick was imported, and when English brickmaking revived in the fourteenth and fifteenth centuries, many of the workmen bore Flemish names.[25] During Elizabethan times, when the price of timber in England rose so high that masonry was no more expensive than wood construction, Londoners built less with timber and turned to brick, just as Paris became a city of stone, which was readily available there.[26] London's enthusiasm for brick buildings and the city's growth caused a multitude of brickworks to appear in the outskirts of the city. In view of a greatly increased demand for brick and high costs of transporting it from other parts, the number of firms participating in the industry increased, and fashion fluctuated among the available colors, which included a variety of reds, a light yellow brown, and a gray that later caught the Georgian fancy.[27]

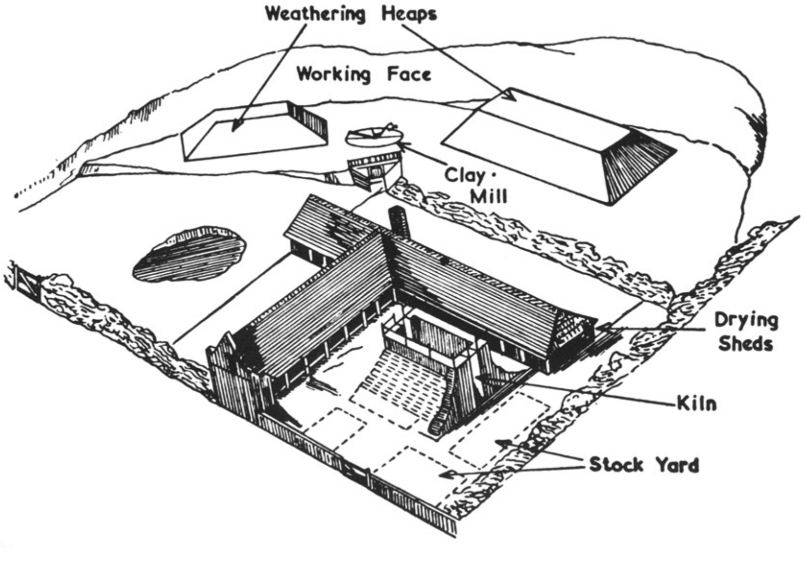
The traditions of brickmaking changed slowly. From Roman times the work had been conducted in a manner that resembled the rural method by which a farmer in the early nineteenth century made his own brick with the help of a local brickmolder, who might follow some other trade during winter months (fig. 2.10).

> When harvest was over, the farmer and his children and hired man would take to the shovel and wheelbarrow and pile the clay loose up to two or three feet high, so that the frost in wintertime might do the disintegrating. Then in the spring the molder would leave his tailor-table and go with his tools to the spot. . . . The raw material would be spread in thin layers over the ground, some water added, and a span of oxen would be driven around and around in the wet clay, doing the pugging, till it was considered ready for molding. The brick molder worked the clay from a table, in single molds without bottom, and his boys or girls carried the filled molds on high edge to the yard, dumping the brick in single rows and returning for another brick. Thus the molder made 2,500 to 3,000 brick in a day, each brick being three inches by six inches by twelve inches in size, sometimes even larger. . . . The kiln consisted of a square hole in the ground, or better, in the side of the hill where one side could be open . . . so as to have ample space for firing.[28]

A more sophisticated and permanent organization was used in 1846, when the Hudson's Bay Company established a brick plant in Vancouver, Canada (fig. 2.11).[29] There the clay was prepared in soak pits, four feet deep and each able to hold enough clay for a molder's daily output. A horse at the end of a sweep drove the pug mill, which was a bin containing a vertical shaft that bore knives to cut any lumps in the clay and work it to a smooth consistency (fig. 2.12). While the horse circled, the molder stood in a pit and took masses of clay as they came from the bottom of the mill. Every cell of a six-brick mold was filled and the excess clay struck off, ready for offbearers to carry the mold to the drying yard, where the blocks of clay were removed from the mold and left to harden in the sun before being stacked in the kiln. After a few hours in the drying yard each brick was bobbed—struck with a flat piece of wood to smooth its surfaces. After a day or two in the sun the bricks were turned for further drying, unless the weather was so sunny and dry that they were ready to make the kiln. A stack of these green bricks was surrounded by previously fired brick over which clay was spread, and wood was brought to commence the firing, which would take 10 to 14 days. A typical simple kiln might hold 20,000 to 50,000 bricks, four to ten days of a molder's work and enough (at 20,000 bricks) to build a small two-story house.[30] Within the kiln, green bricks were stacked in intricate patterns that allowed enough space between them for the hot air to circulate as well as possible, given the need to fully load the kiln. For instance, a rectangular



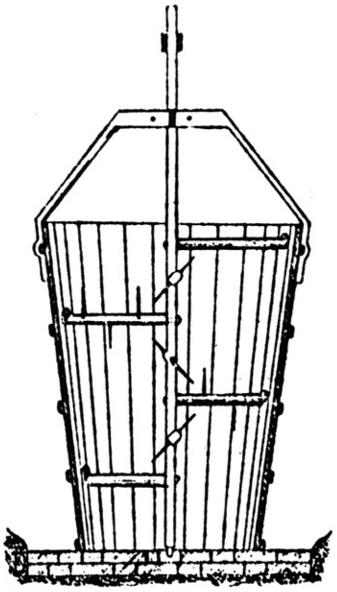
kiln measuring 27 feet by 11 feet by 12½ feet high inside held about 40,000 bricks. Less than 80 percent of the interior volume was occupied by the bricks; the remainder was taken up by spaces allowed at the walls, between stacks of brick, and between bricks in the stacks, an effort to distribute heat within the kiln as evenly as possible.[31] Nevertheless within a kiln the heat was uneven and, even when the firing was most successful, the hardness of its products varied greatly. Those bricks that were not hard enough to be exposed to the weather on outside walls were, because of their color, usually referred to as "salmon" bricks, and they were set aside to be used in the interior partitions of buildings. Those sufficiently fired to withstand weathering were called "common" bricks. The bricks that had received the most intense heat of the kiln and were discolored or misshapen were called "arch" bricks because of their location in the heat-distributing passages that had been built at the bottom of the stack of brick as it was placed in the kiln. The uses of arch brick were those that required impermeability and are indicated by other names applied to them: foundation, cistern, and cellar brick.[32]

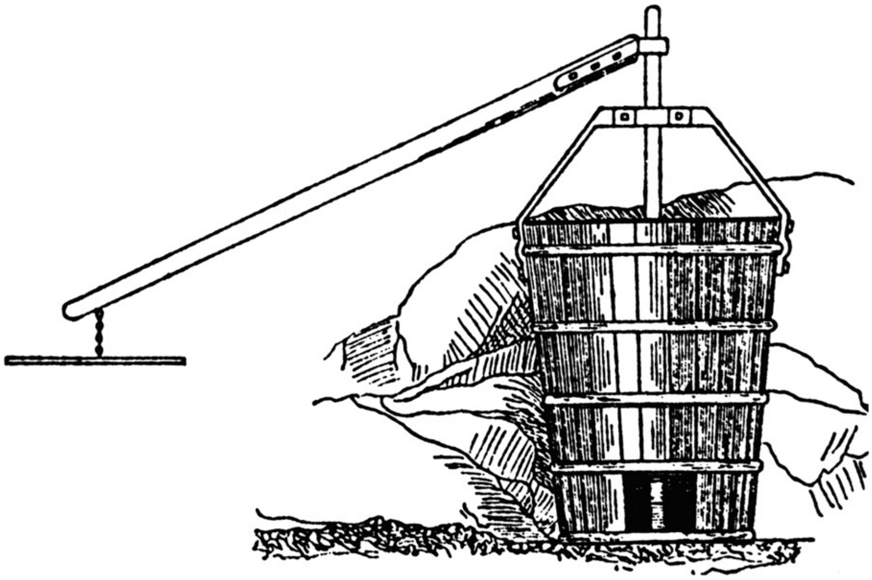


Brick molds, first made of hardwood and later of iron and steel, required treatment by the molder to make certain that the shaped brick would slip easily from the mold. For "sand mold" brick, which had a distinctive surface texture after firing, the mold was dusted with dry sand before being filled with clay, and for "slop mold" brick it was dipped in water. Even after mechanization replaced hand-molding, these processes were duplicated by machines.

By the middle of the nineteenth century, brickmakers had developed mechanical methods of processing clay and forming the bricks that were to go into the kiln. Weathering was often eliminated, and machines prepared the clay as it was dug. The pugging mill was adapted to waterpower and steam power, replacing the horses that had once turned it. For the same purpose, there was the wash mill in which a large trough of clay and water was worked with turning disks. As this process continued, the softened clay ran into a settling basin from which water was later drained. A third machine, the rolling mill, passed clay between two horizontal rollers, and it was sometimes used in combination with other clay-working machines.[33] In many cases, clay was passed through mills more than once in order to insure a fine-textured and plastic material. For some clays these methods did not replace the process of weathering, but at the least they reduced the cost of labor that was required to repeatedly turn over the clay as it lay exposed to frost and rain.

With the seasonal manufacture of hand-molded bricks, molders and their assistants had worked only six or seven months in the year. An English engineer in 1856 wrote of brickmakers,





2.11 From top to bottom, this bird's-eye view illustrates the sequence of work at the typical brick plant of the early nineteenth century. The location was determined by the presence of clay at a point reasonably close to a city or an economical mode of transportation. (A. T. Green and G. H. Stewart, *Ceramics: A Symposium*, 1953. Courtesy of the Institute of Ceramics, London.)

2.12 The vertical shaft in early pug mills bore blades or spikes that sliced and mixed the clay before it reached an opening at the bottom. The shaft was turned by a horse that circled at the end of the rod that extends at the left of this drawing. (A. T. Green and G. H. Stewart, *Ceramics: A Symposium*, 1953. Courtesy of the Institute of Ceramics, London.)

2.13 Leahy's brickmaking machine, available in the 1880s, fed clay through a vertical pug mill. At the bottom, the clay was forced into iron molds around the rim of a wheel. As the wheel turned, the bricks were automatically ejected onto a moving band that carried them away to drying sheds. (*Appleton's Cyclopedia*, 1880, 1:248.)

2.14 In the Imperial brick machine, clay fed into the machine (*A*) was mixed and pressed into molds on the face of large wheels (*C*). As a brick rose to the top position, it was forced out of the mold. This "double machine" was reported to produce up to 100 bricks per minute. (*Appleton's Cyclopedia*, 1880, 1:247.)

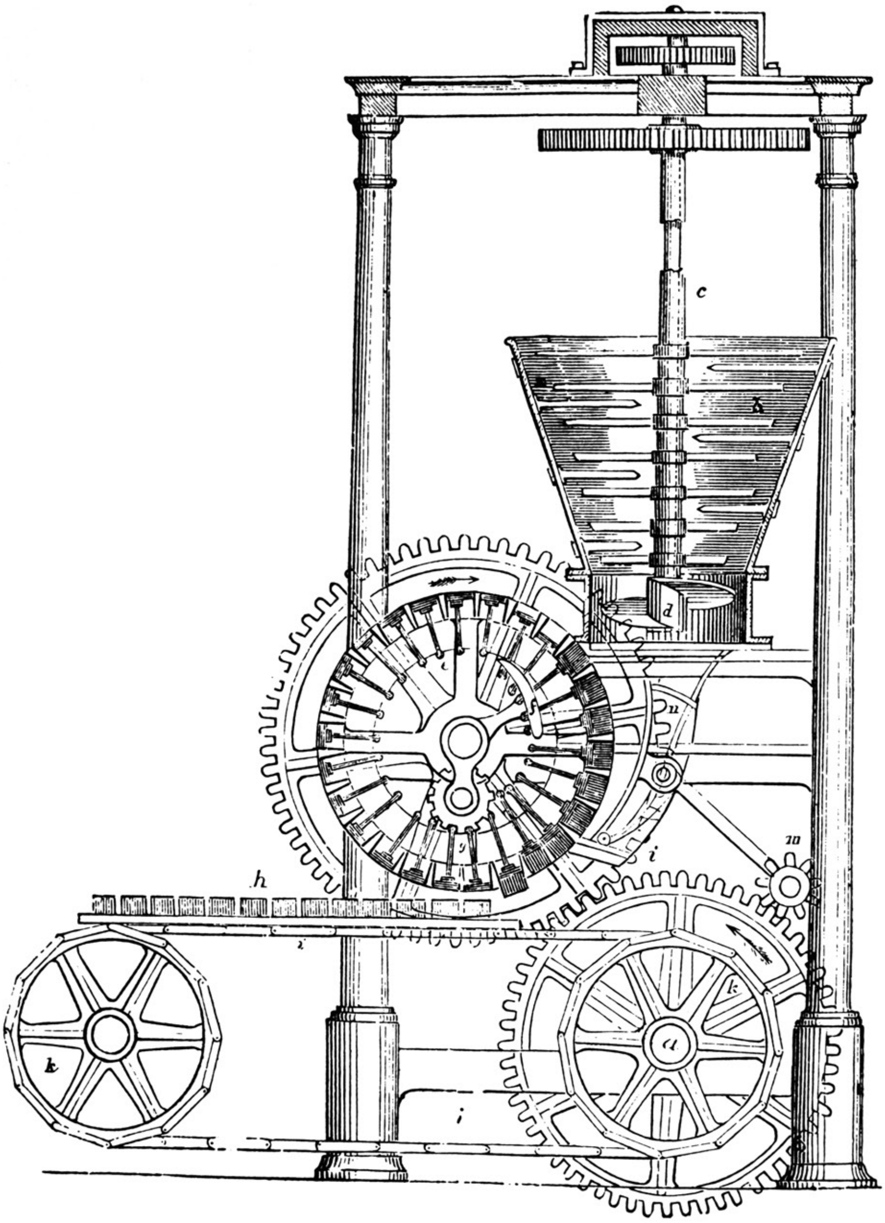
> They therefore work early and late; and from their having no winter occupation, and on account of their dirty and laborious work, they have such a price per thousand as to compensate them. The result is generally, among this class of men, that, although they are so well off in the summer time, they spend all they earn, leaving the winter to provide for itself. At that season, when they require most to sustain themselves and their families, as well as fuel, they have nothing to fall back upon, and in too many instances no employment; for, as they earn so good wages in the summer, they do not willingly come down to the price of ordinary labor. These are the men whom the introduction of machinery will effect.[34]

By diminishing the importance of weathering, brickmaking became much less a seasonal activity, no longer depending on cold weather for preparation of the material and warm weather for sun-drying the bricks before they were placed in kilns.

For hand-molded brick, much effort was required for preparing clay that was wet and pliable. This "soft mud" flowed from the machines, ejected by pressure from the blades of pug mills or by the auger mechanisms within other equipment. The hand molder placed pieces of this clay in molds and compacted them manually, but in the first half of the nineteenth century mechanical means were also found for this phase of the work. Many different machines were developed to apply waterpower or steam engines to the task. In the "soft mud" process, clay was extruded into molds and the machine pressed the clay down firmly and struck off the top of the molds (fig. 2.13). One or more molds were brought against the orifice of the mill for filling and then moved to make way for other molds. Farther along, the molded brick was ejected by the action of a piston set in the bottom of the mold (fig. 2.14).

A machine, introduced in 1835 and later highly developed, extruded stiff clay in a continuous rod having two dimensions of the finished brick (fig. 2.15). Experimentation was required to achieve an even flow of material through all parts of the rectangular die and so prevent the clay being less dense at the corners of the extruded bar, critical points if the brick were to be durable (fig. 2.16). As the shaped band of clay came from the machine, it moved forward on a tabletop to be sliced into bricks either by blades or by frames across which piano wires were stretched (fig. 2.17). Wire-cut brick, although permitting an easily controlled and efficient process of manufacture, had its shortcomings. When the city of Minneapolis in 1898 sought bids for a million bricks to be used in sewer construction, sand-mold bricks were specified because authorities considered wire-cut brick, the only kind manufactured locally, too variable in size, shape, and quality. Despite the specifications, bids for wire-cut brick were submitted, and (probably because of shipping costs) their price proved to be 15 percent below that of sand-molded bricks.[35]

The manufacture of dry-press brick may have been started in the United States almost as early as the start of the stiff-mud process, but dry-press production became increasingly common from 1850 to 1880. (Nonetheless horse-powered soft-clay methods were the most commonly employed in the United States during that period.) The ability to use finely pulverized shale, marl, or hard clay instead of surface deposits of soft clay and the advances made in steam-powered machinery encouraged development of the dry-press system of manufacturing brick (fig. 2.18). Powdered clay or shale, almost dry, was forced into molds under extreme pressure and, as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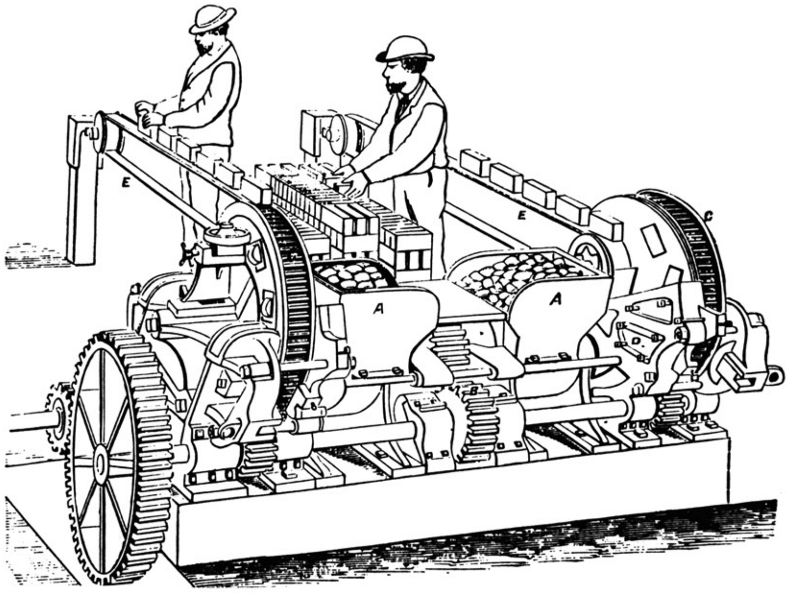
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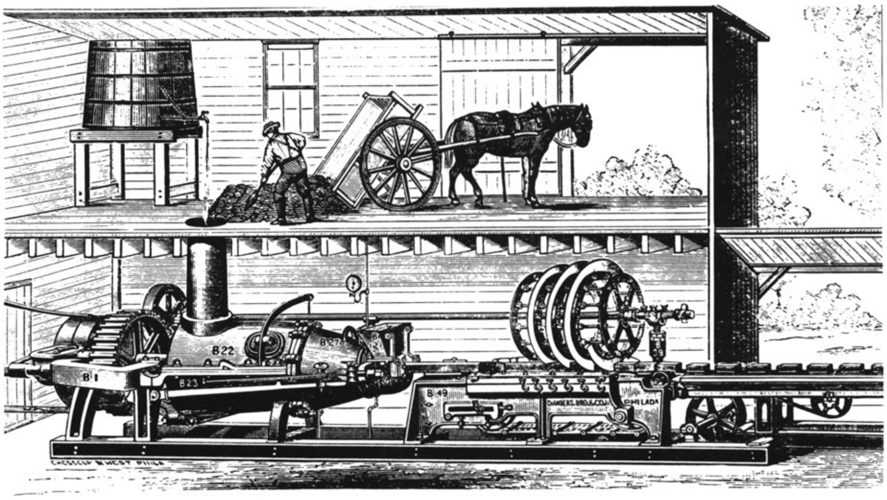
the molds moved from the heart of the machine, bricks were unmolded onto a table, from which they could be taken directly to the kiln without a period in the drying house.[36] Being soundly pressed into cast-iron molds gave the brick a smooth face and precise edges, and sometimes they were pressed a second time to further compact the material.

> The greatest precaution is always observed in handling the pressed bricks before and after burning, much more attention being paid to these bricks than to common bricks. In carrying the bricks to the kiln they are taken up one at a time, placed lightly on the wheelbarrows, and between each course of bricks on edge there is placed a strip of soft wood or a good thickness of some kind of woolen stuff, such as an old blanket. When the bricks arrive at the kiln they are lightly removed from the wheelbarrows, one at a time, and are very carefully handled.[37]

After the Chicago and Boston fires, many architects and builders abandoned the cast-iron, marble, and granite facades that had fared so poorly in reports of fire damage. Hard brick proved in most cases to be better protection against flames, but the usual red brick gave architects of the period too limited a range of expression. In much of the United States the cream-colored brick of Milwaukee was admired, but it was costly even in the vicinity of that city and much more expensive when shipped elsewhere. Red brick from Philadelphia and Baltimore had been the standard for buildings in New York, but in the 1880s production of light-colored brick increased, much of it coming from producers in Perth Amboy, New Jersey.[38] Construction of the exotic Tiffany mansion in New York in 1882 popularized a hard-fired brick of "mottled shades of brown."

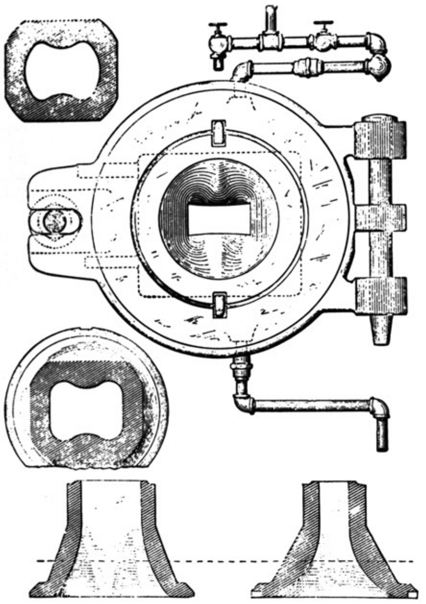
To the search for a variety of color must be added the architects' exploration of "ornamental brick," which could be easily made by shaping the mold in which bricks were pressed. Classical moldings and intricately shaped voussoirs could all be formed of clay, providing ornamentation and detail of the same material as the walls of a building. When pressed brick was introduced into Chicago from Philadelphia, masons were brought west because of their experience in the demanding work of laying it. The popularity of pressed brick in Chicago grew until 1887, when much of it was damaged by a particularly severe winter. Reaction slowed the use of



2.15 Clay was shoveled into the horizontal cylinder of this Chambers brick machine, and water could be added to make a mixture of the desired consistency. As a steam engine outside the workshed turned blades within the machine, the clay was forced along to emerge as a bar of rectangular cross section. A spiral blade cut that bar into bricks. (*Appleton's Cyclopedia*, 1880, supplemental vol.)

2.16 Clay moved unevenly within the dies through which bricks were extruded. In this patented design, the clay entered a channel of curvilinear cross section (upper left) and exited through a section generally rectangular, but slightly narrowed at the center. (*Journal of the Franklin Institute*, January 1883.)

2.17 This "cutting-off" table received an extruded bar of clay from the left. A single wire at left rotated to cut off a length of clay, which was moved on by hand to be cut into ten bricks by a frame of wires. (*Appleton's Cyclopedia*, 1880, 1:246.)

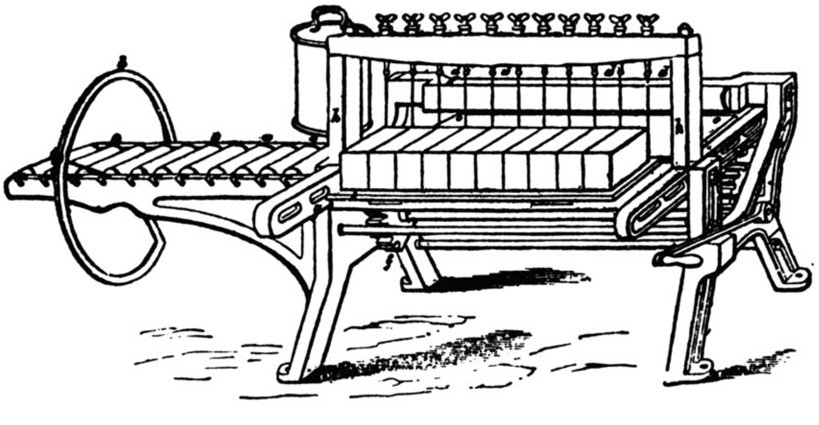


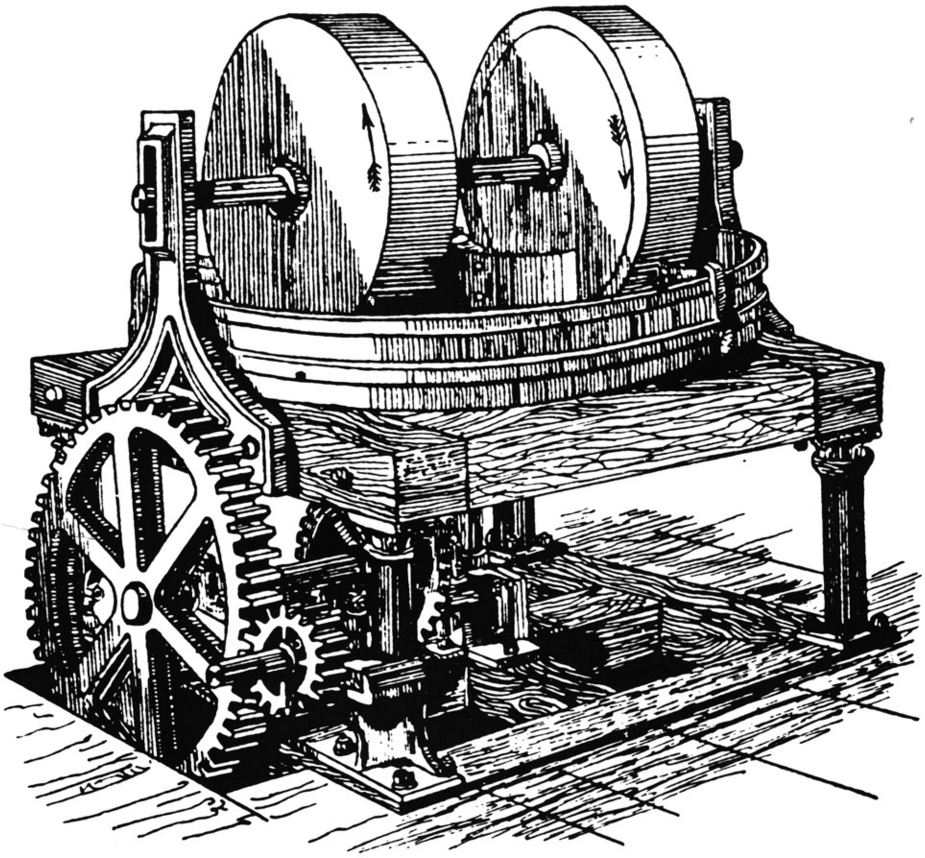
pressed brick in the Chicago area, and in the design of a major civic building brick was abandoned in favor of granite.[39]

With the development of advanced methods for processing clay and shaping bricks came improvements in methods of firing them. The cost of fuel was a major factor in setting the price for brick, and as in other furnace industries the problems were those of achieving economy by mastering the element of time and gaining the greatest possible advantage from the fuel that was expended. The most ancient and elementary form of brick kiln, the scove kiln or clamp, was formed by stacking green brick in the manner described above. After the outside of the kiln was sealed with clay, openings at the sides let fuel be added to the fires, and openings at the top allowed smoke to escape. In order to remove the finished brick, a scove kiln was often simply torn apart, but more advanced types of up-draft kilns had permanent walls and provided grates under the green brick so that heat would rise from a firing chamber below. Although each clamp was used to fire a relatively small quantity of brick, at one time it was estimated that the scove kilns in the United States had as many as a million bricks in them.

Among such intermittent kilns (those that were fired to produce a quantity of brick and later cooled for removal of the brick) were many that varied the locations of chimneys and fires to achieve horizontal or downward movement of heat, but such arrangements did not overcome the fundamental disadvantages of the intermittent kiln. First, much of the fuel was consumed in heating the mass of the kiln itself. As the cost of labor and fuel rose, it was natural that brickmakers should jealously eye the efficiencies that had been developed long before in the furnaces used for making iron and glass. Second, the preparation of clay and the forming of bricks as a seasonal activity was inherently inefficient.

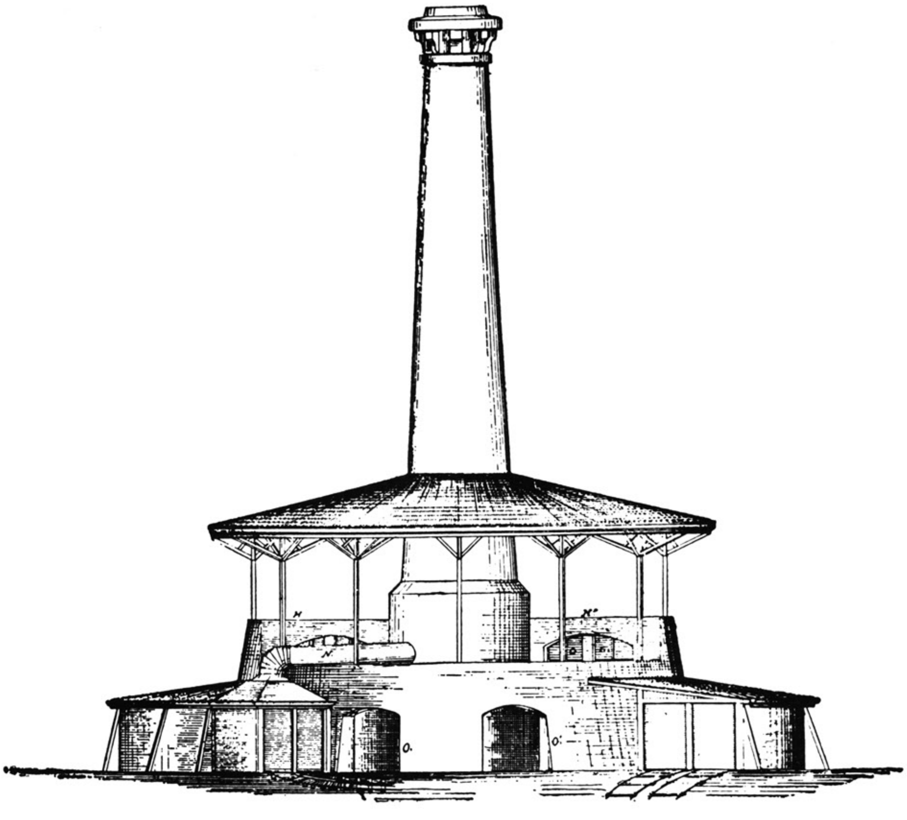
> The "season" closed in the early fall; October was the usual month. The entire summer's product was set in a single kiln. Then came "burning time." This was a





2.18 Mixtures for making brick would often be better controlled when clay was dried and ground to a fine powder before being remoistened. This early form of grinding pan was a roller mill, a basic type that had been used by ancient Romans to grind grain and crush olives. (A. T. Green and G. H. Stewart, *Ceramics: A Symposium*, 1953. Courtesy of the Institute of Ceramics, London.)

2.19 Advertisements for this kiln stated that "radiating and waste heat are used for drying and heating air for combustion." By surrounding the fire with a series of firing chambers, kilns built according to the Hoffman principle were able to operate continuously, directing the most intense heat to each chamber in turn. (*Clay Record*, 29 July 1897.)



> hilarious event. It [was] looked forward to with great interest by certain of the community as an occasion when rum, if ever, was needed to successfully do the job. Everybody then connected with the kiln was happy but the owner of the property; he was commonly overwhelmed with anxiety lest his volunteer help became so utterly drunk as to endanger his kiln by neglect. Such instances were not infrequent. "Boss burners" were in great demand by proprietors of yards, and as the supply of the former was limited and the needs of the latter urgent, there was much rivalry and backbiting over their possession. When one of these "professionals" was secured there was no positive assurance success would attend his efforts. A "good burn" fifty years ago [c. 1840 in Chicago], and even later, was a rarity. It seems more to have been the result of luck than calculation.[40]

Firing in a continuous manner allowed a greater number of small loads in the kilns and thus reduced the risk involved with each firing. With continuous operation of a brickyard, it was possible to assemble a group of workers intimately familiar with their kilns and with the firing characteristics of the clays they used.

The first influential design of a continuous kiln was that of a German, Hoffman, in 1858. It was introduced into Britain about four years later, but as late as 1890 an English visitor reported that this form of kiln appeared not yet to exist in the United States.[41] The Hoffman kiln consisted of a circular ring of kiln chambers with a tall central chimney that was connected to each of the chambers by ducts (fig. 2.19). It was on the level above the kilns that firings were controlled. Fuel could be dropped into any of the chambers, dampers opened or closed to control the intensity of heat in the firing, and openings between the chambers were manipulated to move hot air from one chamber to the next. When a chamber on one side of the ring of kilns was in the midst of a firing, the chamber directly opposite in the circle was cool and being emptied of the fired brick. As workers carried out brick, air to feed the fire entered that chamber and, going through other chambers around the ring, the air was increasingly heated by brick cooling from the previous days' firings. In that way heated air fed the flames, and less fuel was needed to attain the required temperature. Farther around the circle, heat from the fires gradually raised the temperature of green bricks as they approached their turn for firing. At the end of this series of chambers—next to the one being emptied—workmen would be stacking green brick.

Complaints about the Hoffman kiln concerned the limited number of chambers possible around the circle and the inconvenience of stacking bricks in a wedge-shaped chamber. Ovals, oblongs, Ys, Xs, and linear plans were later variations of the scheme, but all were based on the economies possible by sequentially firing a series of chambers. Their popularity was understandable, since the fuel needed to fire a given amount of brick in a kiln of this type was usually less than half that which had been required in intermittent kilns. As late as 1950, it was estimated that about 90 percent of British production of common and face brick was fired in Hoffman kilns or similar continuous kilns.[42]

It was necessary to remove a large part of the moisture in green brick before it could be placed in a kiln, and drying brick was always a process almost as involved as firing it. Drying in the sun was the original and simplest method, but, even in summer, weather made this method unreliable.

About 15 percent of sun-dried brick was damaged and ruined.[43] Roofed drying sheds afforded protection from showers, but they did nothing to relieve the elevated humidity that accompanied rains. Once steam power was introduced in brick plants, the exhaust steam from boilers could be used at night to sustain heat in drying-shed floors, but the construction of iron-floored dryers did little to increase efficiency.

Studies have indicated that the dryers developed later were at least twice as efficient as the "hot floor" method.[44] First there was the tunnel dryer. Its initial form was a coal-fired horizontal flue, extending from the fire to the chimney, in which both bricks and workmen were blackened by the soot. Introduced in 1845, the steam-heated tunnel at first contained wagons of brick moving on rollers, but subsequent designs provided rails on which the wagons moved. It was early recognized that air movement was as important as the heat provided, and fans were installed in the tunnels to make certain that humidity remained uniformly low and the heated air was evenly distributed. A tunnel dryer developed around 1870 exhausted furnace gases through an iron-covered trench in the floor.[45] This caused the heat to be greater where the trench originated and cooler at the opposite end. The rolling wagons of brick and the air that removed evaporated moisture moved in a direction opposite that of the hot gases.

Chamber dryers, a second type, were much like continuous kilns. Hot gases from a burner were channeled so that any heat escaping from the final stages of drying would be employed in the first stages of drying, and the heat released as fired bricks cooled was also used in the work. This system offered several advantages, but the tunnel dryer, in its many forms, remained the simplest to operate.

At about the same time that the tunnel dryer was developed, the tunnel kiln was introduced. In two of the earliest designs, patented around 1850, wagons loaded with brick were moved slowly through a long rectangular chamber. Heat was provided by a furnace at the center and draft by a chimney near the entrance. The top surface of the wagons was covered with slabs of firebrick, but high temperatures within the kilns quickly damaged the metal of wheels, axles, and rails. In an ingenious design of the late 1870s, iron sheets faced with firebrick were mounted on the sides of the wagons and extended into beds of sand alongside the rails. This arrangement sealed off a channel beneath the cars through which cool air was circulated around the wheels.[46] Tunnel kilns were divided into three sections. In the first brick was preheated; in the second it was fired; and in the last the fired brick slowly cooled. This is essentially the action of today's continuous kilns.

All accounts of brickmaking practices spell out the extraordinary range of sophistication to be found among the manufacturing methods that were in use at any given time. There were, of course, contrasts among the procedures used in different climatic zones and variations due to fluctuations of economics and building activity. As a scattered and self-sufficient enterprise, the brickmaking industry long encompassed small establishments with relatively primitive equipment and processes, as well as large companies having considerable technological insight. Since supplies of suitable clay and shale are widely distributed, there was no pronounced geographical concentration of brickmaking activity, and the costs of competitors shipping their brick for long distances often offset the manifest inefficiency of some small local manufacturers.

* * *

In the Byzantine church of San Vitale in Ravenna, the weight of the dome was considerably reduced by using terra-cotta jars, laid in a continuous spiral embedded in the concrete of the dome. Much later, a Paris tile works around 1785 supplied an architect with clay pots that were closed at top and bottom and hexagonal in shape. The pots (about 7 inches high and 4 inches in width) were set in plaster of paris to build floors spanning as far as 12 feet. The results were reported to the Académie d'Architecture, and Victor Louis, architect to the flamboyant Duc de Chartres, adopted this method for rebuilding the Théâtre du Palais Royal, which had burned a few years before.[47] Materials for the new theater were almost entirely noncombustible, and clay pots were used in partitions, ceilings, and a vaulted roof. Louis employed pots in other buildings, and information about this new building system soon reached England.

Sir John Soane used hollow ceramic pots in 1792 in the domes of the Stock Office at the Bank of England, but a greater contribution to the advancement of building methods was made at that time by William Strutt, eldest son of Jedediah Strutt who operated cotton mills in partnership with Richard Arkwright, inventor of the spinning frame. Two years after Victor Louis's construction of the Théâtre du Palais Royal, an architect friend of William Strutt returned from Paris and wrote him:

> [I] ordered one of each sort of the hollow bricks, of which the Arches are composed, to be sent to me, and I expect soon to hear of their being arrived in London. . . . Unluckily I only saw the building the evening before I left Paris, at a time when I was unwell, so that I have not so perfect a recollection of the Plan as I should have had, had I reviewed it at my leisure. . . .
>
> The roof of the Palais Royale is of framed Iron, with the larger sort of hollow brick to fill up the panes.[48]

The following year Matthew Boulton, partner of James Watt, wrote to Strutt about the use of ceramic pots in floor construction:

> I understand you have some thoughts of adopting the invention of forming Arches by means of hollow pots and thereby saveing the use of Timber in making floors, and guarding against Fire. Allow me to say that I have seen at Paris floors so constructed, and likewise at Mr. George Saunders' in Oxford St., London, who is an eminent Architect . . . I have therefore no doubt but it might be applyd also with great success and security to a Cotton mill.[49]

At the time of Boulton's letter Strutt was beginning work on a six-story mill for his father at Belper. In it, vaults made of hollow pots formed the ceiling of the top story, spanning 7 and 8 feet between the timbers that were the bottom chords of roof trusses.

The eighteenth-century use of ceramic pots in floor and roof slabs was intended to lighten those structural elements, reducing the weight that rested on beams and columns yet maintaining the thickness of the slab. It is said that in the 1850s a foreman working on the construction of the Liverpool Exchange proposed that, instead of wooden laths spanning between I-beams, triangular tubes of terra-cotta be used.[50] This combination provided an incombustible floor, but the smooth bottom surfaces of the terra-cotta members proved to be a poor key for the application of plaster ceilings (fig. 2.20).

In the same period, flattened tubes of clay were used in the first story of the Cooper Institute, New York, one of the earliest instances of an iron-framed floor. The system was patented by Frederick A. Peterson, architect of the building, and the terra-cotta was shaped by hand. These tiles spanned about two feet between the iron beams. Little use seems to have been made of Peterson's system. For larger spans, the patent of an English manufacturer of clay products, Joseph Bunnett, provided a shallow arch of tiles with a tie rod across the top to prevent the thrusts of the arches displacing beams that supported them. By this method a room as wide as 12 feet could be spanned with a single vault. After the Chicago fire, an experimental arch of this type was built by architect W. W. Boyington, but it is not known that the system ever found application in the frantic rebuilding of the city.[51]

Around 1860 hollow terra-cotta—or structural tile, as it came to be called—was little used in floor construction. For spanning between iron beams, the more common solutions of that period in the United States were brick arches or curved sheets of corrugated iron filled over with concrete; in England, concrete arches; and in France, light iron bars with a slab of plaster cast between them.

The system patented in England by Maurice Abord, a Frenchman, was much like Peterson's design, although the open cells in Abord's tiles were relatively small. In the English patent, dated 1866, the tiles were shown in use with wooden beams, but a U.S. patent obtained in the same year indicated its application to a span between iron I-beams. The Abord system seems the first to cover the bottoms of the supporting beams and thus fireproof them. This precaution was neglected in a patent of the following year, which produced a flat arch by assembling light tiles made in the shape of traditional voussoirs, the wedge-shaped units that make up an arch. This form is strikingly like the designs that later dominated the field.

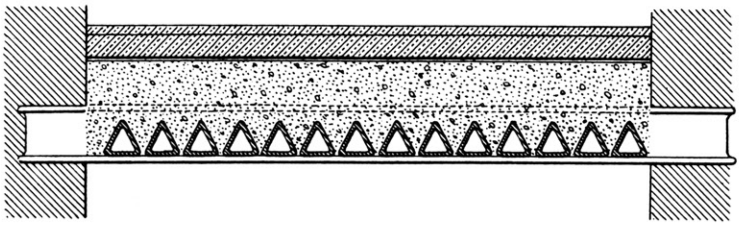
About six months before the 1871 Chicago fire, Balthasar Kreischer, a firebrick manufacturer in Staten Island, New York, and George H. Johnson, a Chicago engineer specializing in the construction of grain elevators, patented a floor construction that was essentially the same as that patented by Peterson 16 years earlier (fig. 2.21). The only significant addition was the provision of grooves on the tops of the tiles to hold wooden runners on which flooring could be nailed. Kreischer tile was used in the Kendall Building and other projects in Chicago and elsewhere, but legal action resulted in a court decision that, in comparison with other designs, the Kreischer patent lacked the requisite originality.[52]

Patent offices were deluged by slight variations of floor arch systems, and lawsuits for patent infringement were frequent. In 1888 an English patent was granted the "Fawcett Ventilated Fire Proof Floor," a system that closely resembled the triangular tiles used almost thirty years before in the Liverpool Exchange (fig. 2.22). The following year a patent of Julius Homan did little more than convert triangular tubes to trapezoidal shapes. When Fawcett sued Homan for infringement of his patent, the defendant charged that at least eleven earlier patents covered all important characteristics of the Fawcett system, and the court dismissed the charges.[53] However, on appeal the decision was reversed on the basis that a new assemblage of old elements qualified for the protection of a patent.

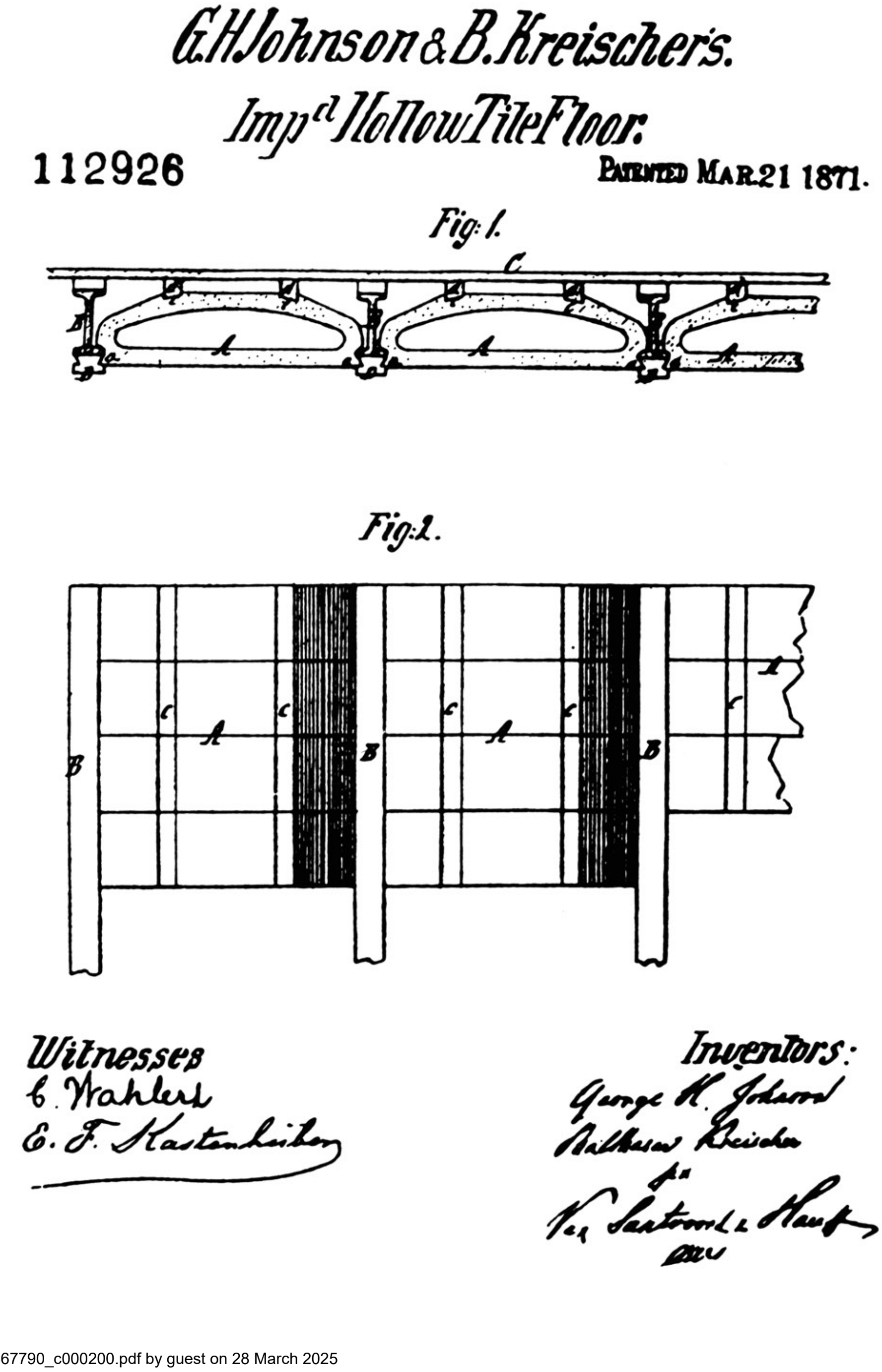
2.20 In construction of the Liverpool Exchange, tubular hollow tiles with a triangular cross section spanned between iron I-beams. This system provided a formwork over which a concrete floor could be poured. Though incombustible themselves, neither the tile nor the concrete protected the bottom of the beams from fire. (*Proceedings, Institution of Civil Engineers*, 1890–1891.)

2.21 More than six months before the Chicago fire, George H. Johnson and Balthasar Kreischer received a patent on a fireproof floor system of terra-cotta. The design was much the same as that used years earlier in the construction of the first story of the Cooper Institute in New York, but terra-cotta "filling strips" were added to protect the bottoms of iron beams. (U.S. Patent no. 112,926.)

The use of concrete at the turn of the century caused a radical alteration in the function of structural tile floor systems. Earlier methods had employed structural tile to bridge between elements of a metal framework; now concrete spanned the distance, as well as serving as the material with which the floor surface was prepared. The Kleine system, first patented in Germany in 1892, allowed generous spaces between tiles. Metal straps lay in the bottom of these spaces and, once concrete had been poured over the assembly, each joint acted as a slender reinforced concrete beam. In such systems the primary function of tiles was to form concrete into an effective structural shape.



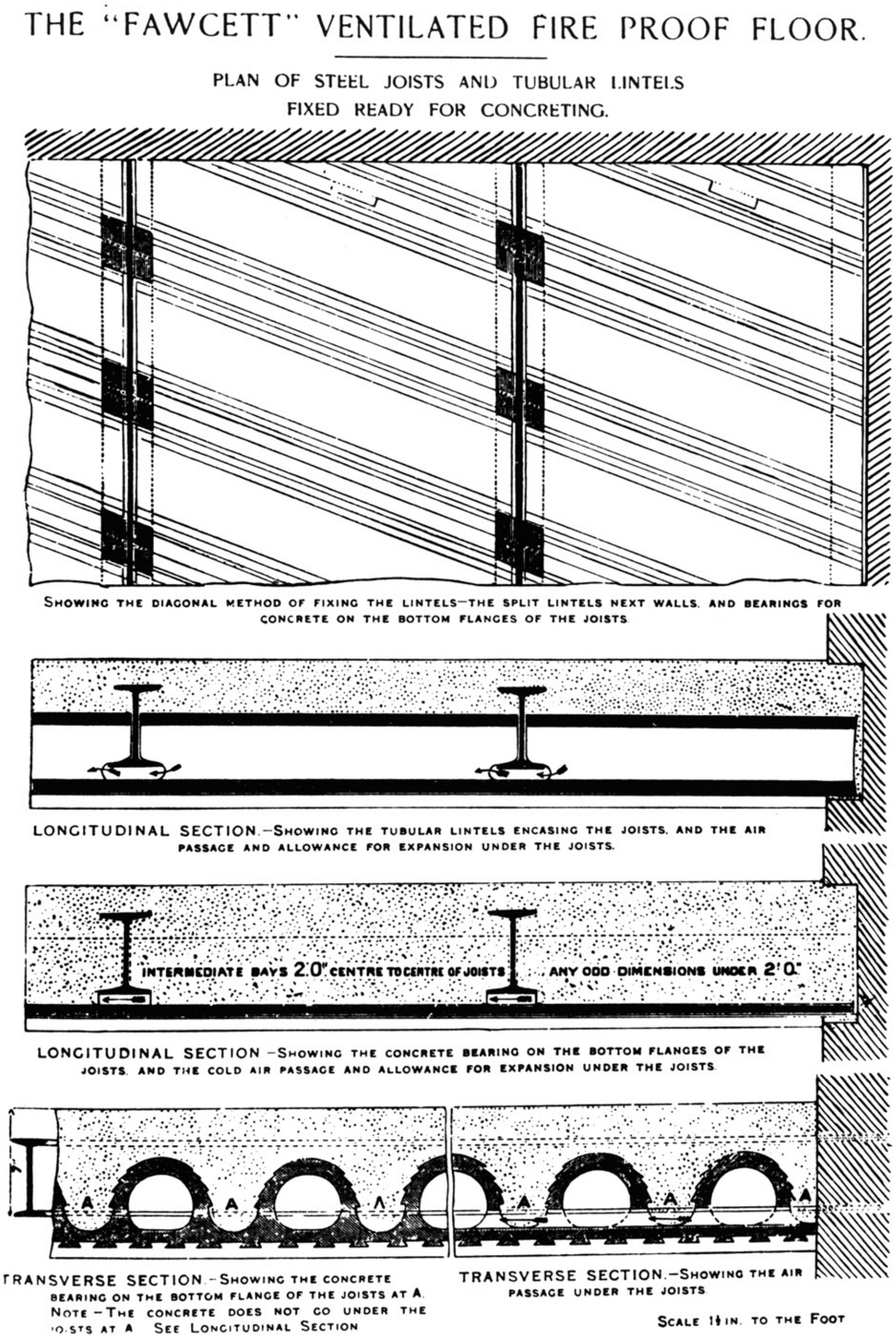
The use of voids in masonry for walls began when an Englishman, Benford Deacon, in 1813 patented a perforated brick that was intended for "conveying air up chimneys from the kitchen fire boiler to the attics, &c., in walls."[54] In his drawings the perforated bricks were shown around a flue, with their perforations continuous so that air warmed within them rose to rooms overhead. The openings were to be cut by hand out of green brick. Little use seems to have been made of Deacon's invention in England, but similar brick later appeared in France, where Prince Metternich saw them and had samples sent for study at the Imperial Polytechnic Institute in Vienna. After a variety of tests to determine the strength of the bricks, a Viennese architect tested them in construction.



Most hollow brick devised in the first half of the nineteenth century had the great disadvantage of being produced by tedious handcraft methods, and because a frequent reason for using light masonry units was the reduction of weight in vaulting and domes, many shapes departed from the traditional rectangular form of

2.22 This illustration from a catalog shows the Fawcett floor system, in which the form of tiles covered the iron beams and provided a passage for air beneath the beams. Placing the tiles diagonally was presumed to simplify their installation, but this method was dispensed with in later years. (*Transactions, British Ceramic Society*, February 1959. Courtesy of the Institute of Ceramics, London.)

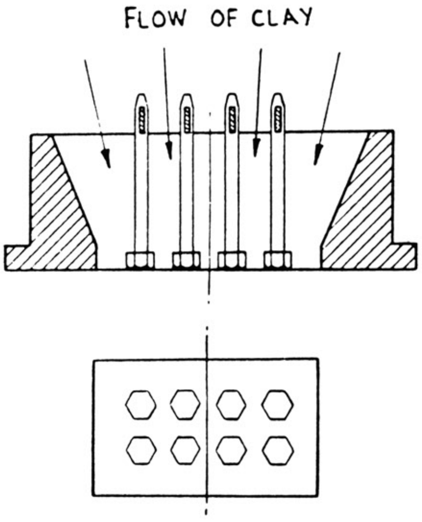
2.23 The first patent of Beart employed a die within which hexagon-headed bolts were suspended from crossbars. Later development of the design improved the flow of clay through the die. (*Transactions, British Ceramic Society*, February 1959. Courtesy of the Institute of Ceramics, London.)



brick. Grooved ends and interlocking shapes afforded an opportunity to make relatively rigid connections in curved roof shapes.

A mechanical means of shaping hollow bricks was patented in 1843 by a Frenchman named Collas. His machine consisted of a chamber that held clay as a piston pressed it through a die. Within the opening of the die, cores were suspended by crossbars, and these produced perforations that ran through the extruded block. Other holes could be punched by hand in the sides of block while the clay was still soft. These additional holes were intended to assure a firm bond between masonry units and the mortar in which they were set.[55]

Two years after the Collas patent, Robert Beart perfected a system making it possible to produce hollow brick economically and efficiently (fig. 2.23). Collas's patent had lapsed, apparently without commercial application, but the Beart patent was soon put to use. Bricks with round holes through their least dimension began to be used by architects. In 1848 Henri Jules Borie obtained a French patent for a machine very similar to that of Beart. After taking out a British patent, Borie exhibited the machine and its products at the Great Exhibition of 1851, where his display attracted attention and won several medals. In order to protect the market for his product, Borie brought suits for patent infringement against almost every manufacturer of perforated brick in England and France and, despite the similarity of his machine and others, Borie's suits were surprisingly successful.



In 1844 Prince Albert fostered the establishment of the Society for Improving the Condition of the Laboring Classes and consented to be its first president. The Honorary Architect of the Society, Henry Roberts, patented a hollow masonry unit suitable for the construction of small houses. Roberts's block corrected these three faults he found in ordinary brick wall construction: bonding between masonry and mortar was often weak, joints running through the wall conducted moisture to the interior, and header courses (bricks with their long dimension extending through the wall in order to tie the two wall surfaces together) were costly of labor.[56] All of these problems were eliminated by Roberts's design, and the size of the blocks (11½ inches long and 3½ inches high) meant that a mason was required to lay fewer bricks, 40 percent fewer in most cases. A model house for workers using these blocks was erected in the vicinity of the Great Exhibition in 1851, and other projects were built for occupancy, including an entire street of houses in the East End of London.

Roberts's block proved to be more expensive than the brick cavity wall, which had originated sometime before 1821. It is reported that by the 1850s about 80 percent of workers' houses in Southampton were being built with cavity walls.[57] The two faces of such walls were held together by either headers or metal ties that extended across the cavity.

McGRAW-HILL

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3

Terra-Cotta

1769	Coade factory commences producing terra-cotta in London
1869	Chicago Terra Cotta Company organized
1870	Terra-cotta imported from England for the Boston Museum of Fine Arts
1871–81	Construction of the Natural History Museum, London, revives the use of terra-cotta
1878	Boston English High and Latin School employs terra-cotta provided by the Chicago Terra Cotta Company
1886	New York Architectural Terra-Cotta Company founded
1920	Twenty-four terra-cotta factories operating in the U.S.

In classical architecture, terra-cotta was principally employed for roofing tiles and floor coverings. Early Greek temples sometimes had ornamental details of terra-cotta and faced brick and wood with tiles, but in later temples stone largely replaced terra-cotta for these purposes. From the earliest times, it was the ease of shaping it that made terra-cotta attractive in architecture. The Etruscans not only used roof tiles but encased beams and covered brick walls with panels of terra-cotta. Since they displayed a liking for terra-cotta sculpture, it is not surprising that their use of the material in buildings was often highly decorative in both pattern and color. Again, the use of terra-cotta—except for roofing and floors—gave way to the brick, concrete, and stone construction of the Romans, although wall surfacing of tile remained popular. Some of these appear to have been fashioned by pressing clay into molds.

Medieval architecture made little use of terra-cotta except for roofing and flooring. The latter, as well as occasional wall tiles, were often stamped with patterns, taking advantage of the clay's potential for decoration. Even roof tiles were less in use at this time, for in much of the medieval world thatch and wood shingles made less expensive roofs. So long as clay pots and jugs were the indispensable containers in everyday life, however, a knowledge of firing and glazing was maintained.

"Artificial stone" was the most common name under which terra-cotta was manufactured in eighteenth-century England. In 1722 Richard Holt and his partner, architect Thomas Ripley, patented "a compound liquid metall, by which artificiall stone and marble is made by casting the same into moulds of any form, as statues, columns, capitalls."[1] Carved stone ornamentation was expensive, and lead casters had long produced work that, when painted, could serve as a less costly substitute for stone. Holt's artificial stone was even more economical, and he appears to have made a good business of supplying architectural details, which could be made according to a client's design or selected from stock patterns. Business was sufficiently brisk to invite competition and to require that he conceal the formula for his mixture of clays and other ingredients. Among Holt's unsuccessful rivals was Batty Langley, a pushy carpenter-builder-architect whom Holt accused of endeavoring to get the secret from his workmen, who were "tamper'd with, decoy'd into Publick-Houses, that being Drunk, they might be the more easily [questioned]."[2]

Holt's company declined and was taken over in 1769 by George and Eleanor Coade, who had come to London from Lyme Regis. The following year George Coade died and management of the factory was continued by either his wife or their unmarried daughter, who was also named Eleanor.[3] Almost as soon as the Coades began operation of the factory, their work attracted the attention of influential buyers. Horace Walpole ordered a Gothic gate for Strawberry Hill, the Twickenham residence he had begun almost twenty years before. Through Walpole, Coade stone became known to his architect, James Essex, and to Sir William Chambers, whom Walpole asked to intervene when Mrs. Coade's bill for the work was higher than expected.[4] Chambers seems to have been favorably impressed with the factory when he visited it in 1772 and, as a Commissioner of the Board of Works and architect to the King, he found occasion to use Coade stone in many designs, such as the twenty-nine urns placed atop the parapet at Somerset

House. Artistic direction of the Coade factory was placed in the hands of John Bacon, who had apprenticed with a London potter and had studied at the Royal Academy. Some of the work was completed by him and the remainder seems to have been done under his supervision, although he continued to be active as a sculptor in marble. Two popular ornaments were the Borghese and Medici vases modeled at two-thirds of actual size from the originals that Robert Adam had brought back from Italy.[5] Many architects employed stock designs selected from Coade catalogs, and often molds for designs executed from architects' drawings were used to add stock designs to the catalogs. The Coade works also supplied ornaments for buildings designed by Sir John Soane almost throughout his career. His orders included bas-relief plaques, urns, figures, many balustrades, and the bases and capitals of columns. After the firm in 1818 began manufacturing *scagliola*, an imitation of the veining and color of rich marbles, Soane and other architects ordered columns shafts of that material.[6] After Mrs. Coade's death in 1821, the plant was continued until it closed in 1839 by William Croggon, a distant relative who had assisted her. A visitor from the *Somerset House Gazette* in 1824 described the conduct of the work:

> Some articles are first formed roughly to give them the external shape in a mould, they are then polished by the chisel while in a soft state, which they endeavor to preserve by wrapping the block carefully in wet cloths. In some cases particular enrichments prepared in matrices are added, and in others the whole is nearly the work of the hand. . . . After the figure is completed in all its parts, it is cut into several pieces for the conveniency of introducing it into the oven, and is afterwards put together, firmly cemented, and iron rods introduced into the arms or other parts that may require to be strengthened.[7]

The result was a work of stoneware, pale cream in color and sharp in detail as a result of carving done as the casting dried. Coade stone and similar terra-cotta products resisted weather excellently. In 1868, almost fifty years after terra-cotta columns and ornamentation were installed on St. Pancras church in London, where four terra-cotta caryatids were mounted around cast-iron columns, a writer contrasted "the sharpness and freshness of the terra-cotta with the worn, bleached, and disintegrated stone."[8] In addition, glazed terra-cotta was washed clean by rain, an important consideration in cities that were growing increasingly smoky.

* * *

The process of making terra-cotta was described in 1896 in the *Yale Scientific Monthly.*[9] The extent to which methods varied through the years or from place to place was minor. Clay was weathered under sheds and then dried, ground, and screened to remove any grit or foreign matter. It was mixed with water, passed through a pug mill, and forced through a sieve; if it were to be used for a slip (a coating to provide a smooth finish to the fired work), it was mixed with large amounts of water so that larger particles would settle to the bottom of the vat. To the clay was added pulverized terra-cotta or firebrick, which limited shrinkage during firing. The proportions used for this mixture varied with the quality of the clay, and sometimes the amount of powder almost equaled that of clay. After being set aside to "ripen," the mixture

was again put through a pug mill in which it was kneaded by rotating blades. Bubbles in the clay were removed by spreading it on a slab and beating it thoroughly with iron rods, and then the clay was ready to be molded.

Molded pieces, those to be repeated often enough to warrant preparation of a matrix, were shaped by pressing pieces of clay into the mold and forming the bracing webs of clay necessary to maintain the shape of the piece. Sculptural work was modeled and then hollowed out to leave a shell, which was cut with a wire into pieces of a size that would be manageable in the kiln (figs. 3.1, 3.2). After being carefully and slowly dried in a warm room, the pieces were placed in a kiln, deeply carved pieces being packed in sand for protection. About 48 hours were required to fill the kiln, an equal time to eliminate moisture in the clay, 60 to 80 hours to fire the clay, and an equal period to cool the kiln slowly—nine or ten days altogether (fig. 3.3). It took only four to six weeks to fill an order for terra-cotta for a small building project after a design was approved, though any delays might interfere with scheduling the construction. In the United States it became the practice of many architectural offices to obtain bids for the provision of terra-cotta before seeking general bids for construction.[10] Natural clay produces white, buff, or red terra-cotta, but minerals may be added to achieve a broad range of colors. In Chicago much of the work was a "grayish buff" produced by a clay dug in Brazil, Indiana, and used to duplicate the Joliet limestone that was popular in the area.[11] Another location provided a clay that baked to a color matching red brickwork, desired for the orders of many eastern architects. The firm of McKim, Mead and White—particu-

3.1 In the modeling room of the Federal Terra Cotta Company, New Jersey, a master craftsman displays a decorative urn. From such clay models were made the plaster molds in which terra-cotta was molded. (W. A. Starret, *Skyscrapers and the Men Who Build Them*, 1928.)

3.2 This photograph of Louis Sullivan's ornamentation for the Bayard Building, New York, has lines added to show the manner in which the design was divided in order to facilitate firing. (*Sites*, no. 13. Courtesy of Dennis L. Dollens/SITES.)

3.3 A view from the 1920s shows the outdoor storage of stock patterns at the Atlantic Terra Cotta Company's works. Each of the kilns seen in the background held 30 to 50 tons of terra-cotta in a single firing. (W. A. Starret, *Skyscrapers and the Men Who Build Them*, 1928.)

larly Stanford White—did much to broaden the range of colors available in terra-cotta and brick:

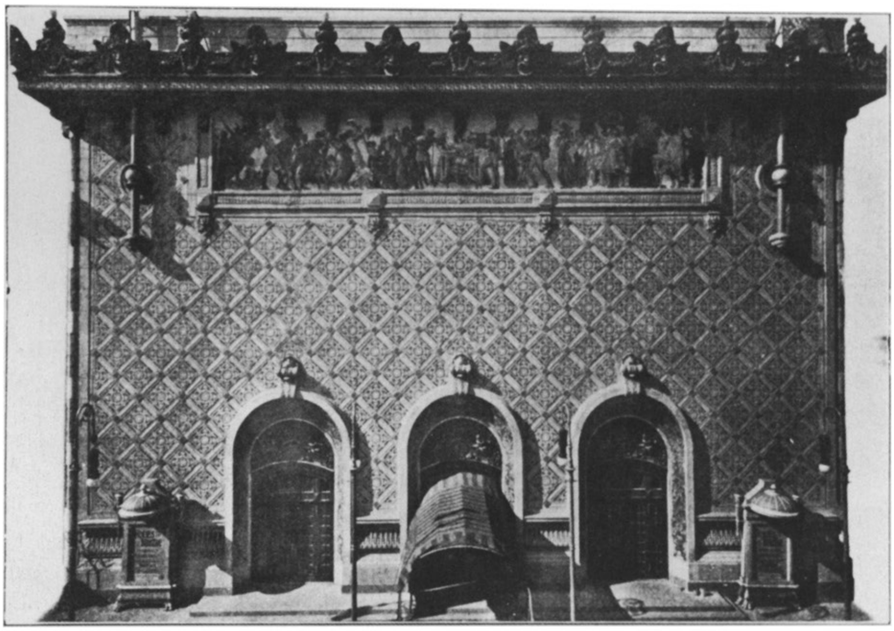
> The late Stanford White, upon one of his visits to the Perth Amboy Plant, to talk over with Mr. Hall a special size Roman brick he wanted made, noticed the bricks used in the Company stable, and in the old Hall residence. . . . He said that was just about what he wanted for color, only with more spots.
>
> . . . They proved a great success, and many large orders followed their use in the Tiffany residence. These bricks were known in the market at that time as "Tiffany Brick."
>
> Some years later, Mr. White gave Mr. Hall a fragment of a Roman brick which he had brought with him from Italy, and asked him to try and match it. . . . They turned out satisfactory to Mr. White, who ordered them used in the Boston Library. This was the origin of the so-called "Old Gold" brick and terra-cotta. . . .
>
> In 1889, McKim Mead and White asked for white terra-cotta. This was made by spraying a buff body with white burning clay.[12]

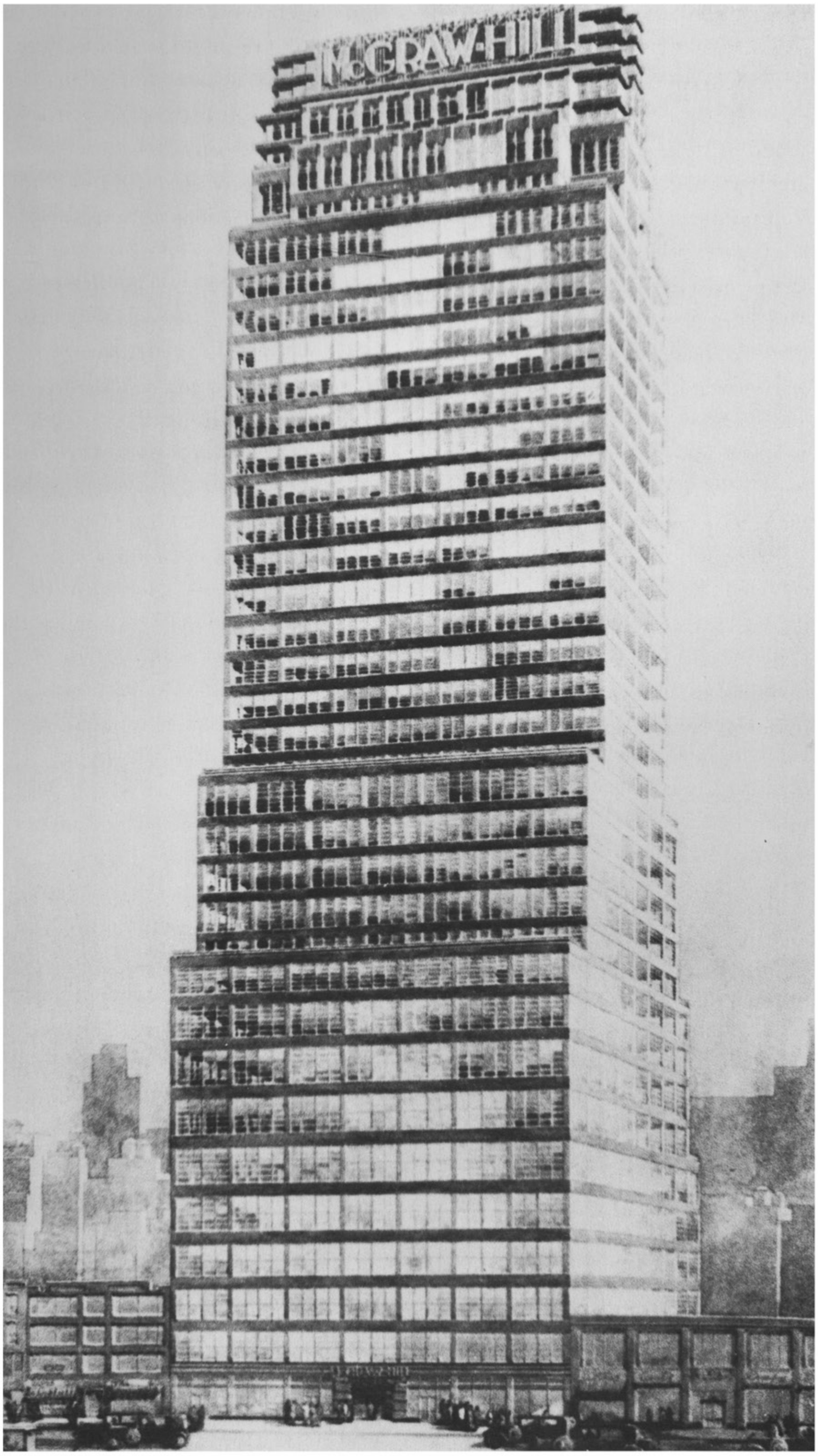
Ridged and scored surfaces, imitating the marks of stonecutters' tools, became popular at one time, particularly among those architects working in the Romanesque fashion of H. H. Richardson.

Through most of the nineteenth century, terra-cotta was employed principally as "artificial stone," an economical substitute for stone carving. Its lightness had proved to be advantageous for hidden uses such as floor systems and fire protection, but when exposed to view it was most often required that the ceramic material resemble stone. There was, in fact, some argument in England about whether terra-cotta should even attempt the fineness of detail that was found in stonework.[13] One group of architects and builders favored the improvement of clay with a variety of admixtures and the use of carving to sharpen details. The other group, mostly associated with projects in the South Kensington district of London, opposed tampering with natural clays and preferred the loose modeling they believed appropriate for clay—leaving more precise forms to the stonemason.

A designer's color preference could easily be satisfied so long as it corresponded to the colors that could result from local clays. In the New York region it was assumed until the 1880s that only red terra-cotta could be produced. Early attempts to produce buff shades were flawed by a portion of each firing taking on a strong pink tone. This was found to be caused by excessively high temperatures. (The science of pyrometry being in its infancy, it was common practice to hang a copper wire in kilns and assume that when the wire melted the fire had reached the required temperature.) Gray terra-cotta was soon introduced, and those three colors dominated the New York market throughout that decade. More exotic colors of terra-cotta and brick were occasionally produced (fig 3.4). However, such variations were usually short-lived, more expensive, and difficult to manufacture. When white terra-cotta was first requested, a slip was sprayed on buff clay, but this coating held soot and soiled easily. A white matte glaze could not be produced, so for a time glossy white finishes were dulled by sandblasting. It was the turn of the century before fresh discoveries in pyrometry and the chemistry of glazes made it possible to produce polychrome terra-cotta at the scale required for extensive use in architecture.

After World War I, a period of prosperity, architectural experimentation, and the wide-ranging exploration





3.4 Although its architectural style is difficult to classify, the Fulton Theater, New York, achieved overall patterns, architectural detail, and even a pictorial frieze through the use of polychrome terra-cotta. (*Architecture and Building*, July 1913.)

3.5 Most of the terra-cotta blocks used in the McGraw-Hill Building (1931) measured about 51 inches by 16 inches by 4 inches. Usually, finished terra-cotta was shipped loosely packed in hay, but the glazed blocks for this project arrived at the construction site in individual boxes of corrugated cardboard and were not removed from their containers until ready to be set in place. (*Architectural Record*, April 1931.)

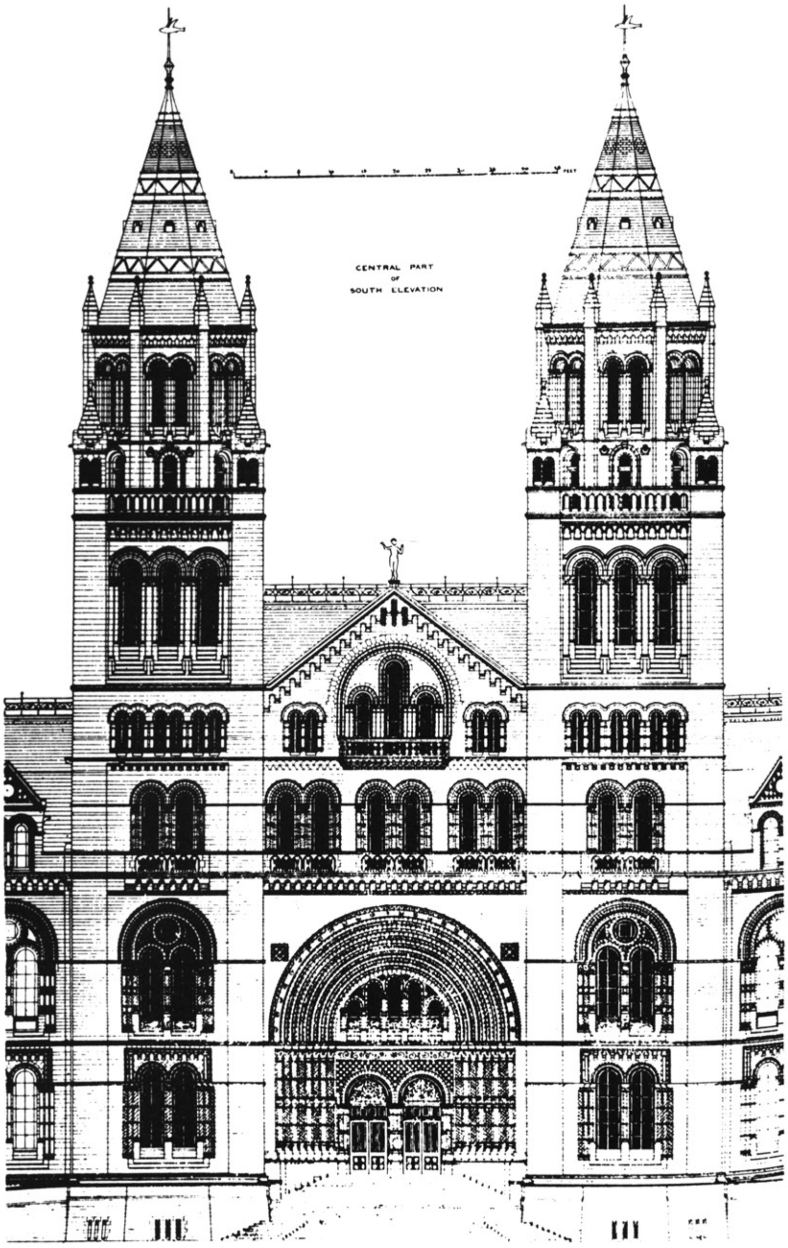
3.6 Construction of the Natural History Museum, London, involved an unprecedented amount of terra-cotta and an unusual variety of pieces. The company that produced the terra-cotta was forced to expand its plant rapidly. For this project's picturesque qualities, blocks were included that had been fired darker than was usually judged acceptable by other architects. (*British Architect and Northern Engineer*, 14 June 1878.)

of eclectic options of style encouraged further development of polychrome terra-cotta. With their need for novelty, movie houses—Classical, Italianate, Moorish, Mayan, and Oriental—proved to be a fertile area for the use of colorful terra-cotta. The Philadelphia Museum of Art (1927) required that companies bidding to supply the terra-cotta needed for its building demonstrate their ability to match the colors that had been determined by intensive study of ancient Greek architectural polychromy.[14]

A building material of this sort, durable yet capable of the full range of coloration, invited painterly experimentation. Peter Behrens, the most influential of German Expressionist architects, designed the lobby of the I. G. Farben Dyeworks as a lavish and fitting display of the artistic use of color. The lobby, entirely of brick, changed gradually from blue-green at the lower levels to yellow-orange at the top—as a painter would create gradations of hue on a canvas. Other buildings employed exterior shading of terra-cotta glazes, usually from dark below to light above.[15] In some designs, bands of brilliant color delineated the forms, framed openings, and accented skylines.

In 1931 the McGraw-Hill Building was nearing completion in New York (fig. 3.5). Thirty-three stories high, this structure was the first major project to be sheathed in machine-made terra-cotta, with blocks forming blue-green spandrels that were about half of the building's wall surface.[16] At the top of the McGraw-Hill Building the company's name was spelled out in orange-and-white terra-cotta letters 11 feet high.

The Natural History Museum in London, part of Prince Albert's plans for a cultural center in South Kensington, pioneered in the use of terra-cotta as the major surfacing material of a building. In 1864 a competition for the design of the museum was won by Captain Francis Fowke, a military engineer who had become something of a specialist in museum design after his work on the Museum of Science and Art, Edinburgh, and the expansion of the National Gallery in Dublin. Execution of the winning design for the Natural History Museum, a massive mixture of various elements from the Italian Renaissance topped with a dome and a dozen Baroque towers, was taken over by other hands after Fowke's death in 1865. The task of developing the design was assigned to Alfred Waterhouse, a young Manchester architect who had only recently set up his practice in London. One of the first changes he made was the conversion of Fowke's design from Renaissance forms to those of the Romanesque. Waterhouse was convinced that terra-cotta should be the major material for the project because of its decorative advantages, lower cost, and resistance to the sooty air of Victorian London (fig. 3.6.). Once the decision on material had been made, a change of architectural style was easily justified. At that time the techniques of making terra-cotta could not assure a uniform product, and small pieces with the variation of color that was natural to the material lent themselves far more readily to the medieval spirit than that of the Italian Renaissance. An additional advantage of terra-cotta was the ease with which it was possible to incorporate a wealth of decoration using the naturalistic forms that had been popularized by John Ruskin and Owen Jones. The opportunity to ornament the Natural History Museum with designs derived



from plants and animals was irresistible. The museum director provided specimens and Waterhouse developed designs for the terra-cotta ornaments, using living material as models for the embellishment of the walls surrounding the zoological exhibits on the west side of the building and extinct models for the geological section on the east side. Much of the decorative work for the Museum was modeled by art students, which reduced costs and may have misled people about the economy of the material.[17]

When James Renwick, a leader of the Gothic Revival in the United States, attempted to revive the use of terra-cotta in 1853, he was assured by masons that the material would not survive the winters of New York. In fact, his terra-cotta lasted very well, but after Renwick had used it on three houses, the manufacturer he had persuaded to execute the terra-cotta work returned to the manufacture of sewer pipes (fig. 3.7). About ten years later Horatio Greenough, the sculptor, returned from Italy with intentions of introducing the use of terra-cotta. After hearing Renwick's account of his experiences, Greenough abandoned the project.[18]

At about the same time, Richard Upjohn, another leader of the Gothic Revival in the United States, employed terra-cotta on two New York buildings. Window trim and cornice details on the Trinity Building, made by another manufacturer of ceramic pipes, lasted well for many years, but the terra-cotta cornice of a bank building, produced by still another plant, was ruined by frost in its first winter. Interest in the use of terra-cotta faltered in New York, and 25 years passed before it was revived.

In Chicago the firm of Hovey and Nichols, dealers in seeds and flowers, decided to enter the business of manufacturing garden urns and statuary as a result of one partner's travels in Europe. They bought a company located in Indianapolis, where coal and clay were available, but soon they discovered that shipping finished ceramics was much more costly than shipping the raw materials required to make them. Consequently, the pottery works was moved to Chicago in 1868. The following year the company was reorganized as the Chicago Terra Cotta Company with a number of new investors that included Sanford E. Loring, an architect who had briefly been a partner of William LeBaron Jenney.[19] New kilns were constructed and the company readied itself for increased production with some minor examples of architectural terra-cotta added to its line of garden furnishings. Loring began to participate more actively in the company; when the superintendent of the works quit, he wrote John Marriott Blashfield, a leading English manufacturer of architectural terra-cotta, asking for his help in discovering a replacement. The letter was passed to James Taylor, one of Blashfield's employees who had superintended the preparation of terra-cotta for Sir Charles Barry's buildings at New Alleyn's College, Dulwich. Taylor, who had already made up his mind to emigrate, thus became superintendent of the Chicago Terra Cotta Company.

The company's plant escaped damage from the Chicago fire in 1871, and it was prepared to take an active part in the rebuilding that followed. Taylor had quickly brought the equipment and procedures to the level of the latest English practices. Sanford Loring withdrew from his architectural practice to become president of the company, and its range of architectural products was rapidly enlarged.

In Boston, competition drawings for the Museum of Fine Arts were submitted in 1870, and a few months later the firm of Sturgis and Brigham was chosen as architects for the project. John Sturgis, son of a wealthy Boston merchant, had studied in England, and five years after establishing his practice he had taken the practical-minded Charles Brigham as a partner.[20] Sturgis spent four years in England during the period when the Museum of Natural History was built and Sir Charles Barry completed New Alleyn's College, both outstanding examples of the use of terra-cotta. It

3.7 James Renwick designed this building in 1853, using terra-cotta for window trim and the frieze of its cornice. Early terra-cotta was unglazed and consequently soiled like other building materials, but 75 years after the building was completed the terra-cotta was described as having "lines as clean-cut as on the day [it] came from the kiln." (*American Architect*, 20 November 1925.)

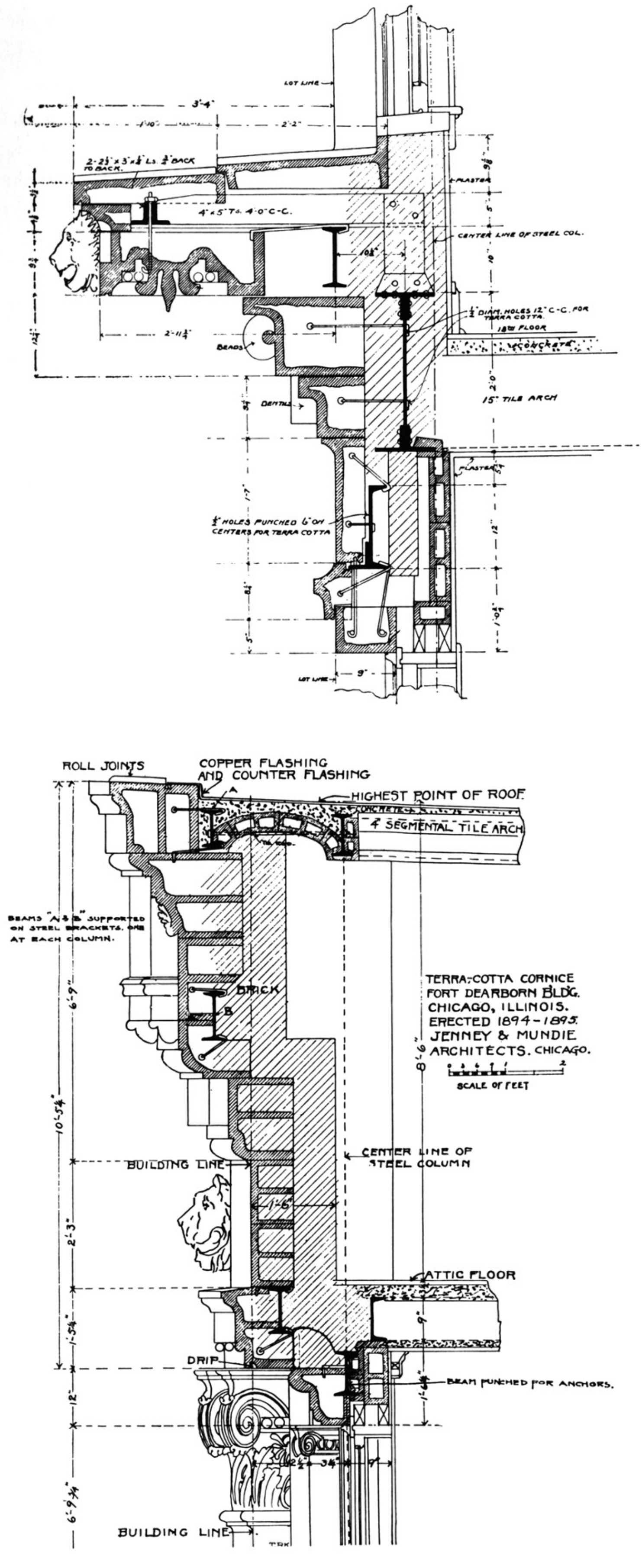
was not surprising that Sturgis recommended terra-cotta for the Museum of Fine Arts, although the material had rarely been used in the United States. When he spoke on the subject of terra-cotta at an annual convention of the American Institute of Architects, Sturgis presented his audience with the equivalent of an elementary textbook on the material, using much of the information that Barry and Blashfield had presented to the Royal Institute of British Architects three years before.[21] When it came time to contract for the terra-cotta to be used for the Museum of Fine Arts, it was Blashfield's English factory that supplied the material, there being no qualified competitor in the United States.

When the Boston English High and Latin School was planned in 1878, the city architect was instructed to use terra-cotta for the building's ornamentation. A short time before, the Chicago Terra Cotta Company had provided trim for two Boston houses, the city's first use of terra-cotta manufactured in the United States. The contract to supply terra-cotta for the school was awarded to the Chicago firm, and Sanford E. Loring, president of the company, hurriedly made arrangements to establish a branch in Boston. Leasing space and facilities from the Boston Fire Brick Company, Loring arranged that all clay required for the project should be shipped there from Chicago, ready for the modeling, molding, and firing to be done in Boston. It was necessary to find someone who would serve as Loring's deputy in Boston and supervise the work. James Taylor had left Chicago two years earlier to settle in New Jersey, where his brother Robert directed the work of the Perth Amboy Terra Cotta Company. James Taylor was persuaded to leave his position at Eagleswood Art Pottery and assume direction of the work in Boston, and after completing the contract for the English High and Latin School he continued his work in that city under the sponsorship of two local investors. Moving from their leased location, the fledgling company built a new plant, but within a short time Taylor left them to assume direction of the Boston Terra Cotta Company, newly formed by merging the Boston Fire Brick Company and another firm.[22]

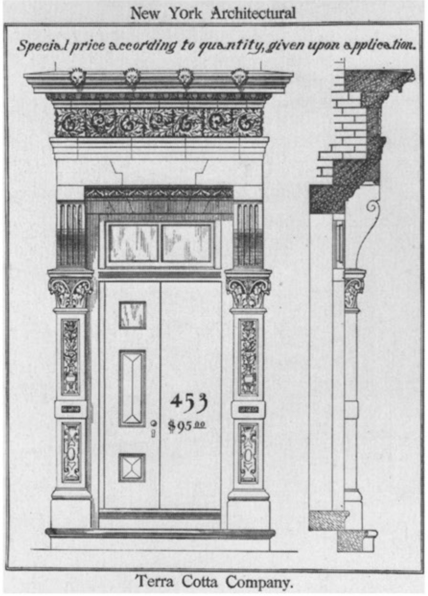
After a building in New York burned in 1882 with the loss of five lives, its owner, Orlando B. Potter, set about building a new structure that was to be totally fireproof in the terms of that period. The Boston Terra Cotta Company supplied over 500 tons of materials for the project, and Taylor frequently encountered Potter at the construction site, for the owner was in the habit of keeping a close eye on the progress of his building projects. A New York guidebook of 1892 provided a description of the new Potter Building:

> It has eleven stories, and was the first building in the midst of the great newspaper section to be erected of such a height. The Potter Building possesses two unusual features: first, it was the first office building erected in this city which was ornamented elaborately with terra-cotta; second, it was the first to have the iron and stone work covered with hollow bricks as a protection against fire. It is one of the most substantially constructed and fireproof office buildings in the city. The owner so ordered its constructions that it would endure practically forever.[23]

The Potter Building was also the last tall building constructed in New York without using a steel skeleton. During their encounters at the building site, Taylor convinced Potter that there was an opportunity for a new company to manufacture terra-cotta in the



3.8 **In publishing details of terra-cotta cornices, William LeBaron Jenney stressed the importance of filling the backs of terra-cotta pieces wherever possible. Cornices with strong projection, popular at that time, were usually supported by cantilevered I-beams, and soffit pieces of terra-cotta were held in place with metal hangers. (*Brickbuilder*, June 1897.)**



3.9 Standard architectural ornamentation could be offered by manufacturers of terra-cotta. As with cast-iron building fronts, repeated use of molds was necessary in order to recover their cost, and the custom designs made for architects often found their way into catalogs of stock designs. (New York Architectural Terra-Cotta Company, 1887.)

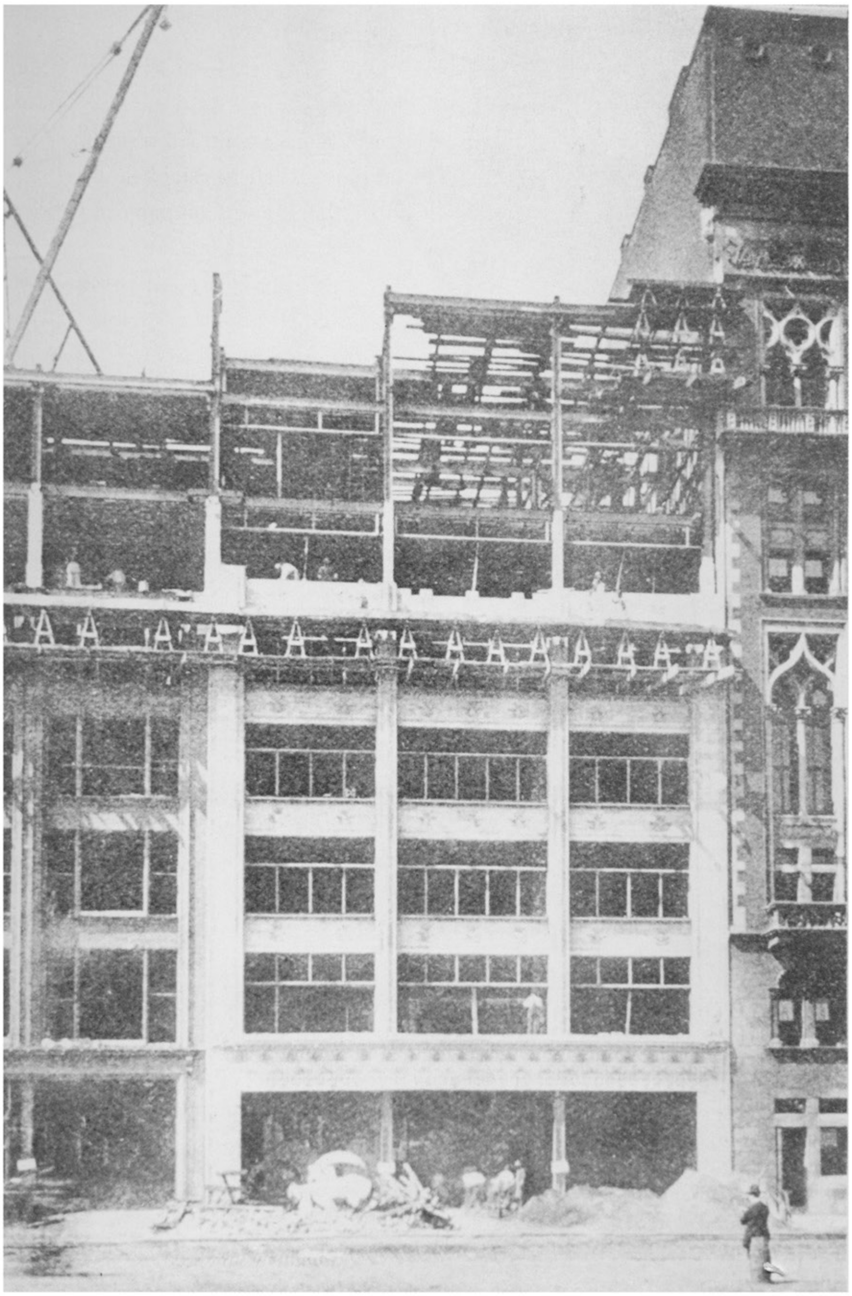
3.10 Terra-cotta was well-suited for sheathing steel skeleton construction, as in three adjacent buildings for wholesale millinery companies in Chicago. The firm of Gage Brothers and Company agreed to pay additional rent to compensate for the employment of Louis Sullivan, Chicago's master of terra-cotta ornament, to design the facade of their portion of the structure. (*Brickbuilder*, December 1899.)

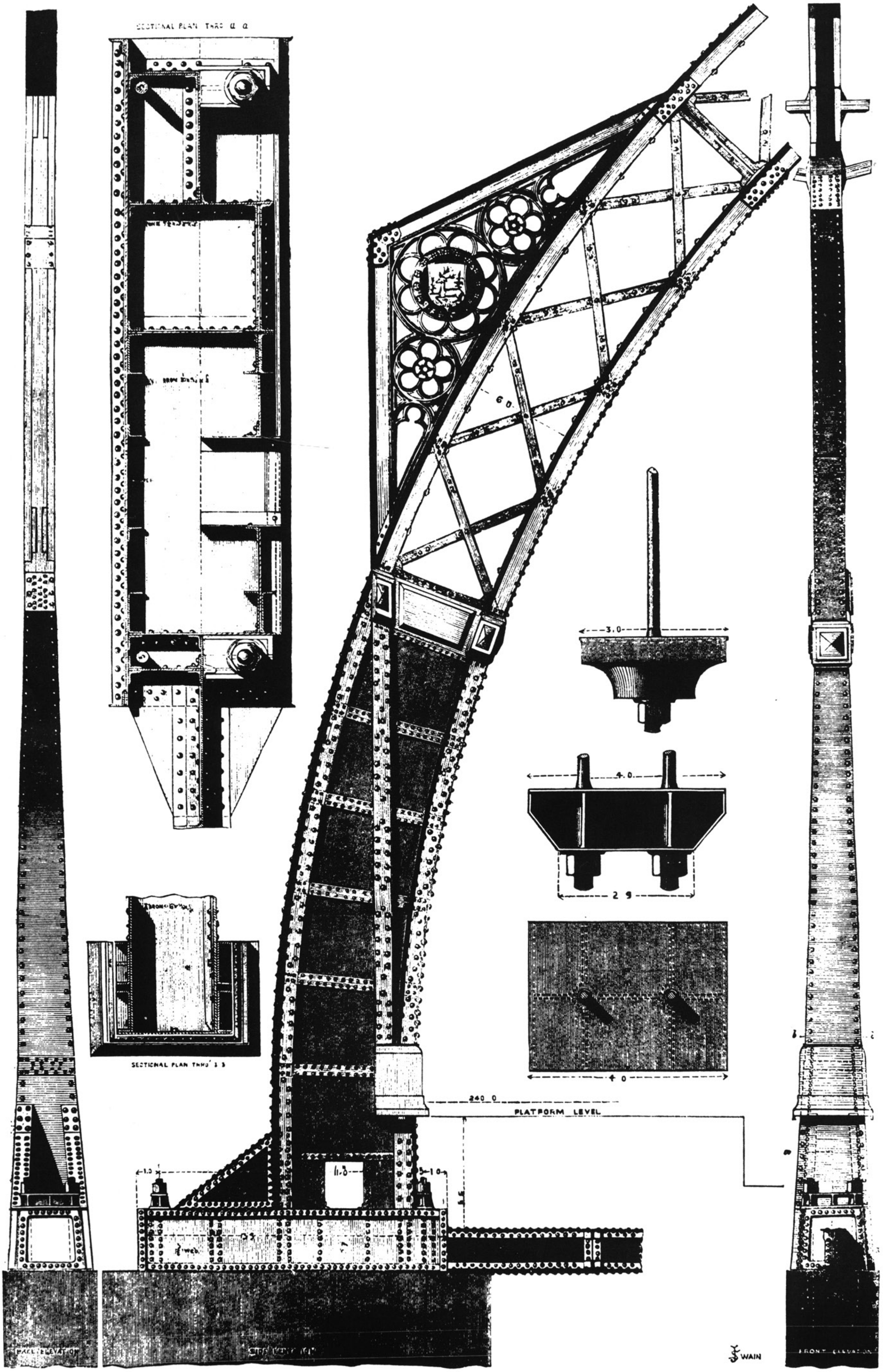
New York area, and in 1886 the New York Architectural Terra-Cotta Company was formed with Potter as one of two partners and James Taylor as superintendent (fig. 3.9).

The revival of terra-cotta in New York had begun in 1877 when George B. Post designed a residence on 36th Street using red terra-cotta shipped from Chicago.[24] The first public building to use terra-cotta and the first significant contract of the newly organized Perth Amboy Terra Cotta Company was the Brooklyn Historical Society, another work of Post, who led New York architects in their experimentation with terra-cotta ornament. His order of terra-cotta for the Product Exchange Building (1882) totaled over 2,000 tons and required the Perth Amboy company to construct additional kilns and workrooms and hire more craftsmen, some attracted from England. Of the other architects who employed terra-cotta decoration, few tested its potential for elaborate ornamentation as thoroughly and consistently as F. H. Kimball, who used intricate Moorish detail for the Casino Theater on Broadway and developed friezes depicting American Indian life for the Montauk Club, Brooklyn, in 1890.[25]

Shortly before the Chicago Terra Cotta Company established its Boston branch to fulfill the English High and Latin School contract, a group of its employees left to establish True, Brunkhorst and Company in Chicago. Sanford Loring's management of the Chicago Terra Cotta Company soon collapsed, leading to the company's failure in 1879 and Loring's return to architectural practice. Its competitors, retitled as the Northwestern Terra Cotta Works, fell heir to the clients that Loring had developed over the preceding years. Other manufacturers of terra-cotta were soon launched, and by 1920 there were 24 companies operating from Atlanta, Georgia, to Seattle, Washington, and 28 other companies had failed, merged, or withdrawn from the brisk competition.

The depression of the 1930s took its toll. The orders received by major U.S. terra-cotta manufacturers in 1933 were but a tenth of those received a decade before.[26] When building activity resumed after World War II, terra-cotta had become a curiosity. Other materials, including cast stone, were available for architectural elements, and fashion had abandoned the ornamental work for which terra-cotta had been so well suited. Its high labor costs hampered its competition with other materials more adapted to mechanized production.

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4

Iron and Steel

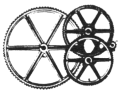
1709	Coke employed in smelting iron
1781	The relationship of carbon content and the strength of steel is discovered
1783	Use of rollers to bind lumps of wrought iron introduced by Henry Cort
1784	Henry Cort produces wrought iron by "puddling"
1796	Cast-iron beams and columns used in a Shrewsbury mill
1809	Cast-iron dome covers the courtyard of the Halle aux Blés, Paris
1835	Construction of the iron fishmarket behind Hungerford Market, London
1849	Installation of the first cast-iron facades produced by James Bogardus
1851	Crystal Palace, London, and Lime Street Station, Liverpool
1855–56	Henry Bessemer and William Kelly patent processes for the manufacture of steel
1859	Three-high rolling mill awarded a patent (Britain)
1879	Standard shapes for rolled steel established by German manufacturers
1884–85	Construction of Home Insurance Building, Chicago, often credited as the first example of skyscraper construction
1889	Galerie des Machines, Paris, employs arches of wrought iron
1893	Chicago regulations limit building heights to ten stories

4.1 **Diderot's *Encyclopédie* shows a blast furnace of the late eighteenth century. Iron ore and fuel were placed in the tall brick furnace. Water-powered bellows (below left) insured a hot flame; molten iron flowed out at the bottom (above center). The heart of the furnace would usually last about 30 weeks before it required rebuilding, but if the outlet for molten iron became plugged for a short time a new furnace could quickly be ruined. (Diderot, *Encyclopédie*, 1762–1777, "Forge," plate 2.)**

Although iron had been as precious as gold during the Mycenaean period of Greek history, in later centuries it became more available.[1] The structural use of iron in Greek buildings is limited to a very few examples in connection with beams and many applications in masonry walls and columns. In beams, rectangular iron bars, as large as 36 square inches in cross section, were set in grooves at either the top or bottom of the stones of architraves, and they apparently served as additional beams, supplementing or safeguarding the load-bearing capacity of the stone beams. Such uses are relatively rare, but much iron was to be found within Greek walls. In both walls and columns, iron dowels guarded against horizontal movement between stones, just as iron cramps hooked a stone to those that were placed beside it. Molten lead was poured around such dowels and cramps to insure their fitting snugly in the holes and grooves carved for them. I-shaped cramps in the walls of the Parthenon measure about a foot in length and 4 inches in width, and appear to have been heated when they were placed in grooves partially filled with lead.[2] Although concrete and the arch were the mainstay of Roman builders, iron continued to be used as dowels and cramps in their masonry.

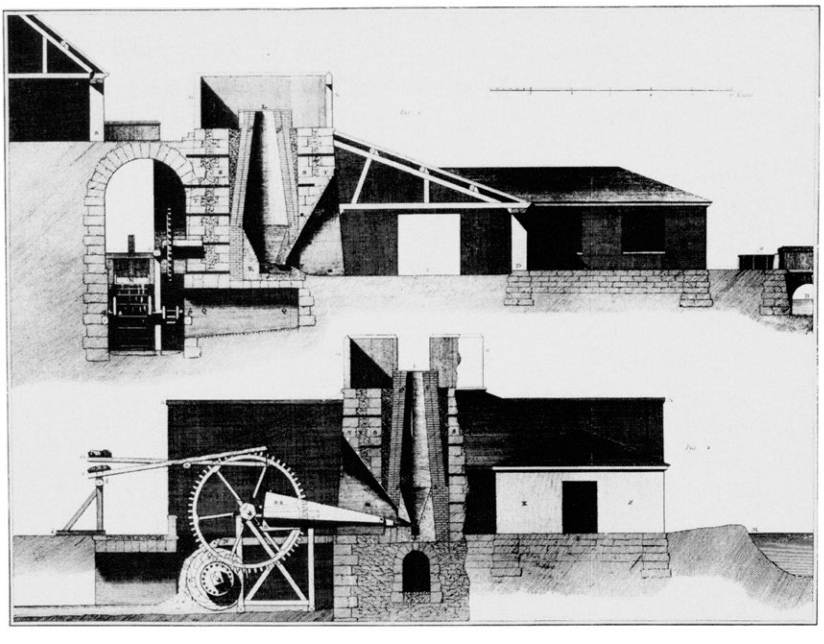
In medieval buildings, iron played an important role within the fabric, usually hidden but sometimes visible. Rods between piers and columns stabilized the work, and at the Sainte-Chapelle (Paris, 1244–1247) curved straps were fastened on each side of voussoirs, "holed to take the ends of round iron bars like the rungs of a ladder."[3] The most intricate of Gothic work required considerable augmentation with iron. For a large window at Westminster 126 cramps were furnished, weighing a total of 143 pounds.[4] To deter rust, which endangered masonry as it expanded, it is said that iron was boiled in tallow, just as linseed oil was applied to stone that did not weather well and resin was sometimes used in mortar. In addition, records indicate that iron was painted with pitch, varnished, or dipped in tin to protect it from rust.[5]

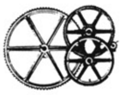
Rods within masonry often took the form of complex frameworks knitting together the stones. In the spire of Salisbury Cathedral, iron bars were linked together to reinforce the structure. Christopher Wren in 1669 wrote of the iron bars in the spire: "These [are] so essential to the standing of the work that, if they were dissolved, the spire would spread open the walls of the tower, nor could it stand one minute."[6] Outward thrusts imposed on walls by vaults, domes, and other roof shapes remained a problem through the Renaissance. The elegant high melon-shaped domes favored by Baroque architects followed the precedent established by Filippo Brunelleschi's dome for the Florence Cathedral, where three iron chains were set in the masonry to counteract outward thrusts of the dome. In supports and buttressing for such ambitious constructions, carefully designed systems of tie-rods and cramps guarded against the strains produced by settlement of the structure and the prêssure of winds. Even in wood construction the supplementary use of iron assumed a critical role, with connections replaced or supplemented by iron straps. In all of these cases, however, iron served as an assistance to a major structural material. Only later did the production of iron advance sufficiently for it to become a major material of building.



Cannons were the major product of the English iron industry in the sixteenth century, but toward the end of the century governmental regulations limited the production and export of cannons and severely restricted cutting wood for fuel, in order to make certain that timbers would be available for shipbuilding.[7] Ironmakers, accustomed to making charcoal by cutting away the forests surrounding their furnaces, were soon forced to purchase fuel from charcoal makers, who planted acorns and other nuts to produce crops of small trees which they harvested to produce charcoal. The process required covering a hemispherical mound of logs and branches with earth or sod, igniting the wood, and controlling the heat by adjusting an opening at the top of the mound. Charcoal was the usual fuel for smelting until the eighteenth century, for it provided a high temperature with no smoke and little ash. Although experiments were often made in the use of coal and peat, neither of these fuels proved successful at that time. Every fuel contained oils and minerals, which were less troublesome for other trades in which the fuel and the raw material were kept apart. In smelting, on the other hand, fuel and ore were stacked together and impurities in a fuel strongly influenced the quality of iron produced. Therefore, charcoal became the principal fuel of iron smelters in ancient times, and when charcoal became scarce and expensive, attempts were made to find another fuel for the furnaces. Brewers, who had found that using coal to dry malt produced a foul-tasting beer, began in the 1640s to employ coke made from coal by methods quite similar to those by which charcoal was made. It was more than a half-century before coke would be used to smelt iron.

Abraham Darby, operator of a Bristol brass and iron works, in 1707 leased iron furnaces at Coalbrookdale in Shropshire. There he began to manufacture iron pots and kettles according to his patented method of casting them in molds of sand. In 1709 Darby started to use coke in firing his furnaces. The iron furnace of that period consisted of a vertical cavity in a large mass of masonry with water-powered bellows to inject air at the bottom (fig. 4.1). Alternate layers of charcoal and ore were laid in the cavity. Smoke went out an opening at the top and melted ore ran down through the bright coals and flowed out at the bottom of the furnace. Once lighted, a furnace was charged at the top with additional fuel and ore, the firing continuing day and night until the masonry deteriorated and it was necessary to build a new furnace. Besides being much less costly than charcoal, coke was less likely to crumble, and this made it easier to maintain the flow of air through larger and taller furnaces. Because the molten metal ran down a greater distance through the fuel held in a larger furnace, it became hotter, more liquid, and more able to fill fine details of any mold into which it might be poured.

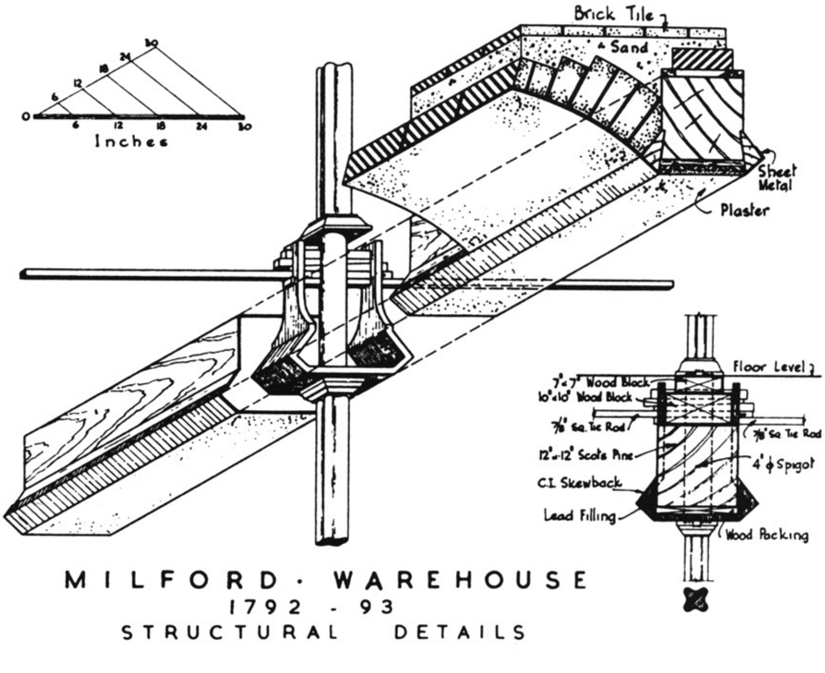




The development of metal-framed buildings can best begin with the history of English textile mill construction at the end of the eighteenth century.[8] The typical textile mill of the period was five or six stories high with heavy walls of masonry. Timber beams spanned between the walls, supporting wooden joists and floor boards. The width of mills was usually about 28 feet, sometimes a single span but most often having one or two rows of intermediate columns, and the length was usually around 120 feet. With wooden floors, lanterns, lint, and oily machines, the risk of fire was great, and high insurance rates encouraged mill owners to investigate metal construction.

William Strutt in 1792 planned a cotton mill for his father's hosiery factory at Derby. In plan the building was a traditional mill, six stories high with masonry walls. On the top floor, shallow arches made of hollow clay pots were set between the bottom members of the wood trusses. This eliminated the need for columns on that floor. On other floors cast-iron columns divided the width of the mill into three spans of 9 feet. In nearby Milford, a four-story warehouse built by Strutt was constructed in a similar manner with plaster covering the bottoms of the wooden beams and sand and tiles laid as the floor (fig. 4.2). The heavy timber beams were bored to receive metal pieces that connected the top of one column to the base of the column above. In this way shrinkage of the wood beams did not alter the structure. Tie rods between the column heads provided lateral bracing. The structure of the Milford warehouse was protected more on the basis of flammability than fire resistance. While timber beams were shielded from flames, the cast-iron columns were left exposed.

The wooden beams employed at Milford had triangular strips of wood fastened along their bottom edges to hold brick arches. The use of iron beams with similar projections characterized a second phase of English mill construction. In a flax-spinning mill built in 1796 at Shrewsbury, iron columns and beams were combined. The



4.2 In Strutt's Milford warehouse, cast-iron columns were connected vertically by short lengths of metal and laterally by tie rods. Sheet metal and plaster protected the lower side of the wooden beams. (*Transactions, Newcomen Society*, 1955–1956.)

beams were vertical plates, 11 inches high, that thickened on the bottom to provide a triangular portion, 5 inches wide at the base. The shape suggests that it was designed as a seat for brick floor arches much more than it implies any structural understanding of iron beams.[9] These beams extended over four spans of 9½ feet and were cast in two pieces, which were bolted together a short distance to one side of the center column.[10]

Twenty years later, with the use of iron beams and the improvement of their shapes, the floor area that could be supported by a single beam's span and a single column was doubled. This advancement effected distinct savings in the cost of the iron needed for mill construction, the cost of the material having been a deterrent to broader adoption of iron for that purpose, and it allowed greater freedom for the mill operator's arrangement of machinery. Once the use of iron beams had been tested and accepted, the next phase in the development of metal construction was the theoretical understanding of the beams themselves.

Early in his career, before he became deeply involved in the design of ships and bridges, William Fairbairn designed two English textile mills. In 1824, when work on these mills began, Thomas Tredgold published the second edition of his *Practical Essay on the Strength of Cast Iron*, reporting on the experiments he had made. His proposal as the most efficient shape for iron beams was a slender I-beam (fig. 4.3). Tredgold erroneously assumed that cast iron was equally strong in tension and compression, whereas it is about five times stronger in compression. His I-beam had only slightly more of its metal at the bottom, where tension stresses are present, than the narrow inverted T-beams used over twenty years before. In one of his mills Fairbairn employed a beam 18 inches deep at the center of a span measuring 20 feet.[11] During the same period Eaton Hodgkinson, a British mathematician, began an intensive theoretical study of beam action, and in conducting tests to corroborate his theories he was aided by Fairbairn. Hodgkinson's analysis of the action of tension and compression within a beam proved to be accurate. According to his calculations the ideal beam shape would have had a small upper portion to take compression stresses and a heavy lower portion to take tensile stresses, the two connected by a thin vertical plane. Such differences in the dimensions of a casting would have cooled unevenly, causing stresses within the material, and therefore the theoretical shape had to be adapted to the requirements of its manufacture. This adaptation was often the case during the period before cast-iron structural units were supplanted by those that combined cast iron for compressive stresses with wrought iron for tension.

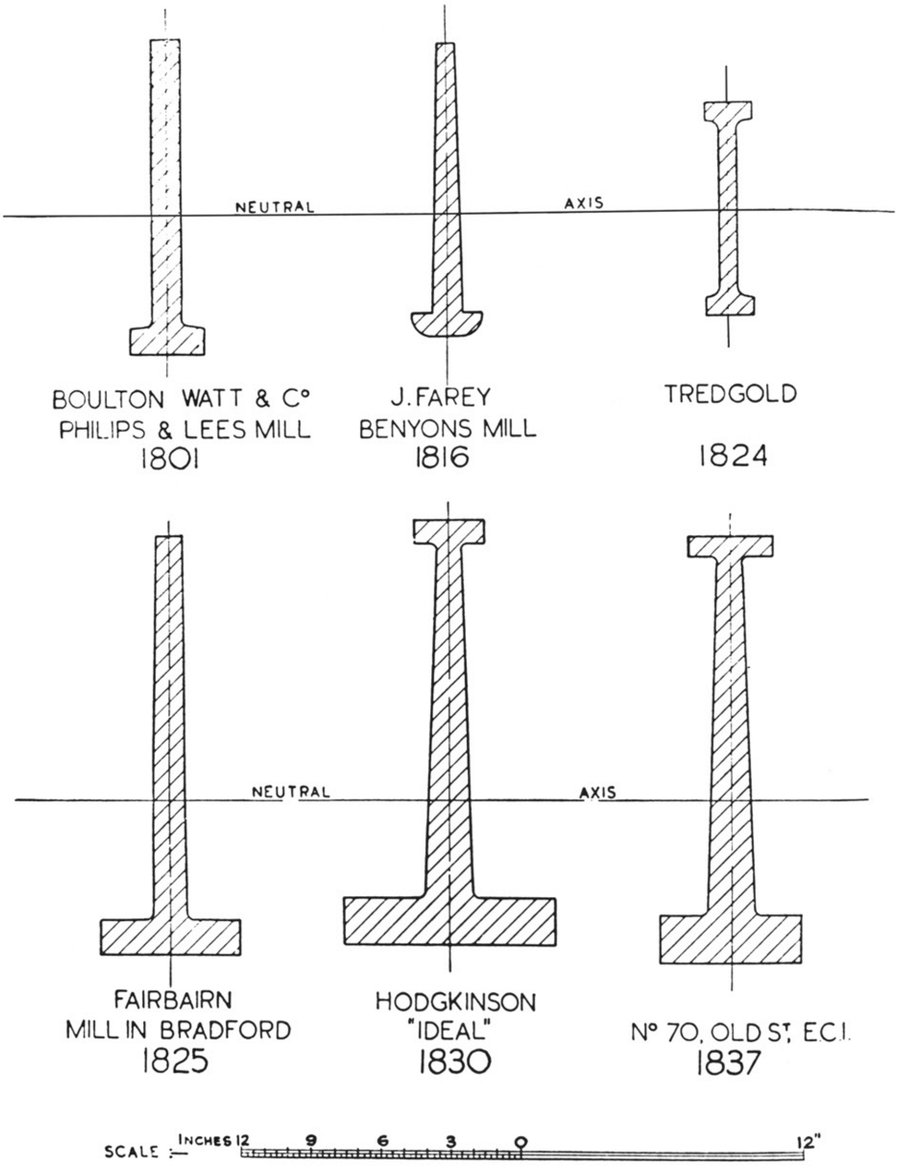
When work began in 1887 on the alteration of the old grain market of Paris for use as the Bourse de Commerce, an inscription was discovered on one of the columns:

> Philibert Delorme, architect, in 1540 conceived the idea of a wood framework; this system, long neglected in Paris, was used for the first time in the construction of this dome in 1782.
>
> That structure burned in 1802 and was replaced in 1811 by the present dome.[12]

The original Halle aux Blés, built in the 1760s, was a circular building arranged around a circular courtyard about 130 feet in diameter. Its simple facade, with tall arched openings at

4.3 **These sections of cast-iron beams demonstrate by their shapes the increased understanding of beam action and the low tensile strength of cast iron. (*Transactions, Newcomen Society*, 1940–1941.)**

4.4 **The metal dome of the Halle aux Blés rested on the inner wall of the ring-shaped building. The iron dome built in 1811 copied the form of a wooden dome built almost 30 years earlier. (*Construction Moderne*, 21 December 1889.)**



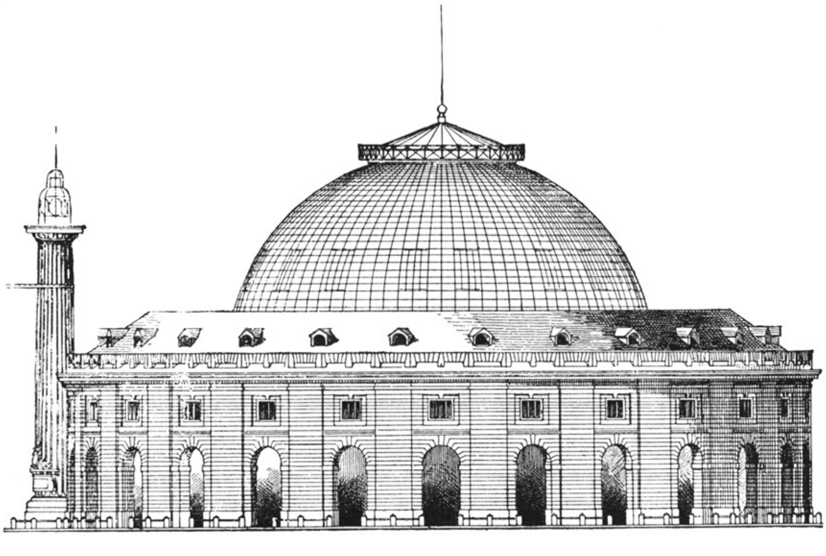
ground level, was interrupted only by the incorporation of a Doric column 90 feet high, which had served as an astrological observatory for Catherine de Medici's palace on the site. Over 15 years after the market was built, it was decided to roof the courtyard so that it could better serve for storing and displaying grain and flour. In 1782 proposals were sought for roofing the courtyard. François Joseph Bélanger submitted a design for a dome of iron; two other architects, Molinos and Legrand, together presented a scheme for a wooden dome. The wood design, which followed a drawing of Philibert Delorme, was executed. This was the wooden dome that burned in 1802.

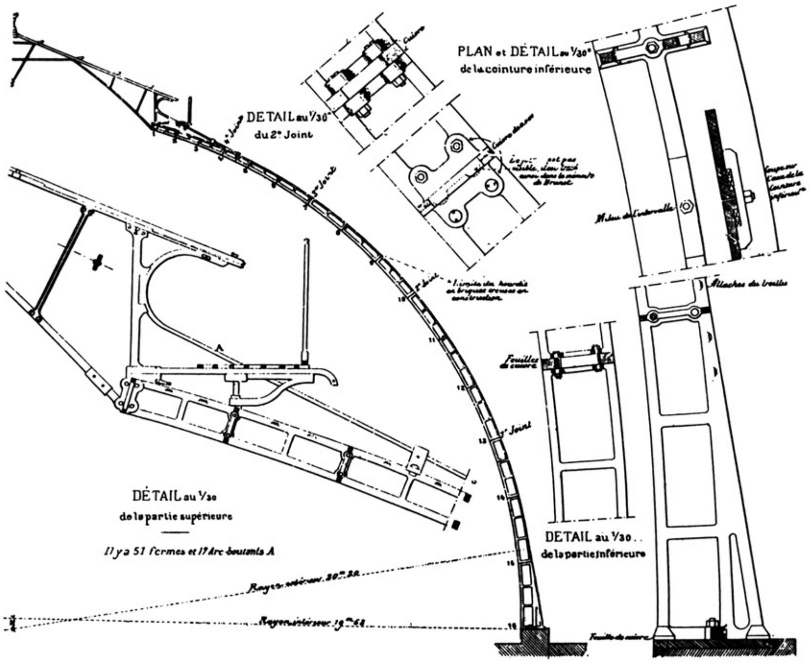
Five designs were submitted for replacing the wood dome of the Halle aux Blés, but all were rejected as impractical.[13] Later Bélanger submitted plans for an iron dome, and it too was based on the scheme published in 1540 by Delorme.[14] Cast iron was chosen as the material by the Minister of Interior because it was considered much more economical than wrought iron.[15] This decision seems to have been strongly influenced by Napoleon's enthusiasm for iron construction and the high cost of the wrought iron that had been used over a decade before in the construction of the Théâtre Français. The dome for the Halle aux Blés was practically as large as that of St. Peter's in Rome, and it was long a major monument of Paris (fig. 4.4).

Even while its new dome was being planned by Bélanger as architect and J. Brunet as engineer, the development of new market facilities for the grain trade began to diminish the use of the Halle aux Blés.[16] In the 1880s it was decided to convert the building to a stock exchange, and during the process of reroofing the dome its construction was carefully studied, since none of the original drawings remained. The dome was made of 51 ribs, each divided into 6 castings of iron (fig. 4.5). Fifteen horizontal rings of cross bracing tied the ribs, and a sixteenth formed the base of a lantern about 37 feet in diameter. Thick plates of copper were placed in the connections of the castings so that the soft metal would compensate for any unevenness of the surfaces being joined.[17] Careful examination after 75 years showed no deterioration other than a crack in the bottom ring of cross braces and rust in the dome's lantern.

The dome of the Halle aux Blés was no doubt a model for the cast-iron dome of the London Coal Exchange, built in 1849. While the Coal Exchange dome had a diameter of 59 feet, less than half that of the Halle aux Blés, its ribs were integrated with a variety of ornamentation in the cast iron that continued on supports and the railings of galleries. The lower half of the dome in the Halle aux Blés had been obscured by an allegorical mural; a much smaller band was plastered at the bottom of the Coal Exchange dome, and this band was divided into panels, allowing the lines of the ribs to continue to the supports.

Although the use of iron and glass to roof narrow passages between





shops had been developed in France during the latter half of the eighteenth century, it was principally the English architect Charles Fowler who exploited metal in the design of markets. In 1826 Fowler built the Covent Garden market, combining a stiff Greek Revival facade with a fruit market roofed by glass held in ribs of iron. A little later he built Hungerford Market, which was demolished in 1860 to make way for the Charing Cross railway station. While this original building of Hungerford Market was stone, roofed in timber, in 1835 Fowler used iron to cover a fish market located behind in a courtyard facing the Thames (fig. 4.6). The span of 32 feet and cantilevers of 6 feet were roofed with sheets of zinc, mounted on pieces of tarred felt to avoid electrolytic action between the two metals.[18] Lateral stability was provided by diagonal rods in the clerestory and iron brackets at the heads of the columns, so that the structure of the market roof required no masonry walls or piers to maintain its rigidity. Fowler designed other iron market buildings, but in the church he built at Honiton, Devonshire, he confronted the difficulty of using metal in a more finished space. The church's nave was spanned by iron members with tile and cement filling between. When parishioners gathered in the church during winter months, the heat and moisture that rose from them caused condensation to form on the iron ribs and drops of water fell on the heads of the congregation. It was necessary to add a roof of more customary construction.[19]

Metal construction of market halls was to be found almost everywhere by the end of the nineteenth century. This was principally the result of Napoleon III's construction of the Halles Centrales in Paris. In 1853 the emperor halted construction of a masonry market building so formidable that it was referred to as "The Fortress of the Marketplace."[20] In its place the same architects, Victor Baltard and Félix Callet, about a year later began construction of a market building made of iron. Baltard's design provided the light and air needed; as the first market to serve so large a population, it became a model.

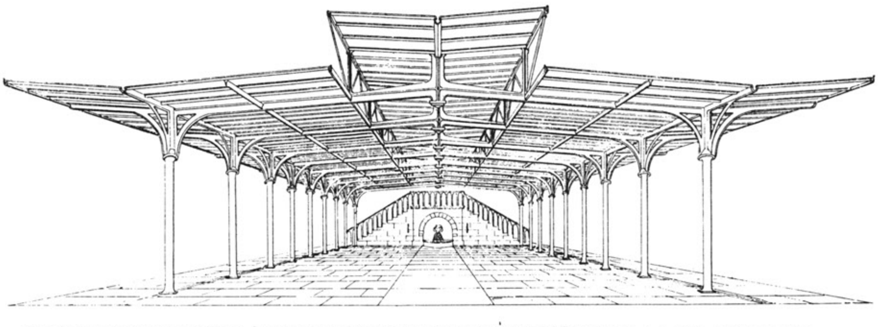
The ability of cast iron to assume decorative detail was most often exploited by direct imitation of stylistically traditional castings that assumed the appearance of stone. Sometimes the shapes took on thinner dimensions when formed of cast iron, dimensions far from those typical for stone, but even then paint might be mixed with grit to give a stonelike texture to the surface of the iron. This was common in the cast-iron facades manufactured in the United States by James Bogardus, Daniel Badger, and others. In 1836 Bogardus had gone from New York to London, where he promoted his engraving machine, one of his many inventions (others included a sugar-grinding mill, several clock designs, and a gas meter). It seems reasonable to assume that during the four years he spent in England, he would have become familiar with Fowler's use of metal in market halls as well as with the other experiments in iron construction. Bogardus continued inventing when he returned to New York, focusing much of his attention on grinding equipment. By 1847 his manufacture of milling machines had grown sufficiently to require a larger building. Foundations were laid, but work was halted while Bogardus prepared cast iron for the facade of a five-story building, the other parts being constructed of brick and timber. A row of three storefronts followed. The castings for these projects were made by four different foundries, according to patterns of Classical derivation that were provided by Bogardus. He stressed the ability of cast iron to reproduce decorative detail: "Were only a single ornament required, it might perhaps be executed as cheaply in marble or freestone: but where a multiplicity of the same is needed, they can be cast in iron at an expense not to be named in comparison, even with that of wood; and with this advantage, that they will retain their original fullness and sharpness of outline long after those in stone have decayed and disappeared."[21] When these projects were completed, work was resumed on Bogardus's workshop, a five-story structure occupying the standard New York lot of 25 by 100 feet. Its cast-iron facade was made in the same design as had been used on the storefronts that came before it. After completing his own building, in 1851 Bogardus prepared the arches and columns on the facade of the Baltimore Sun Building, according to a new design by the New York architect Robert G. Hatfield.

Preparation of cast-iron building panels was relatively simple compared with the accuracy required to cast and prepare machine parts, but the work of planing and grinding the surfaces that were to be joined was a major cost factor. (Earlier the English had solved this problem, though not well, by filling joints with "rust cement," a paste made with iron filings, sal ammoniac, sulphur, and a little water.) After the small-scale drawings of the architect were completed, the foundry's work began:

> Large scale drawings are made, followed by full-size drawings of the principal parts. Then the patterns are prepared. In the foundry the pieces are moulded in sand and castings are made. Cleaning, chipping and filing next follow. The ends of the cast columns are cut off true and smooth in a double-ended rotary facing machine. In the fitting shop, the columns are laid on their backs, spaced the right distance

4.5 Details for the 51 ribs of the dome for the Halle aux Blés, Paris. Note the thick pads of copper that were inserted at the points where sections of a rib were bolted together. (*Construction Moderne*, 3 November 1888.)

4.6 Charles Fowler chose to use cast iron in the Hungerford wholesale fish market because he believed it would be more sanitary and less odorous than wood or stone. Structural members also served as gutters, and alternate columns served as roof drains. (*Transactions, Royal Institute of British Architects*, 1835–1836.)



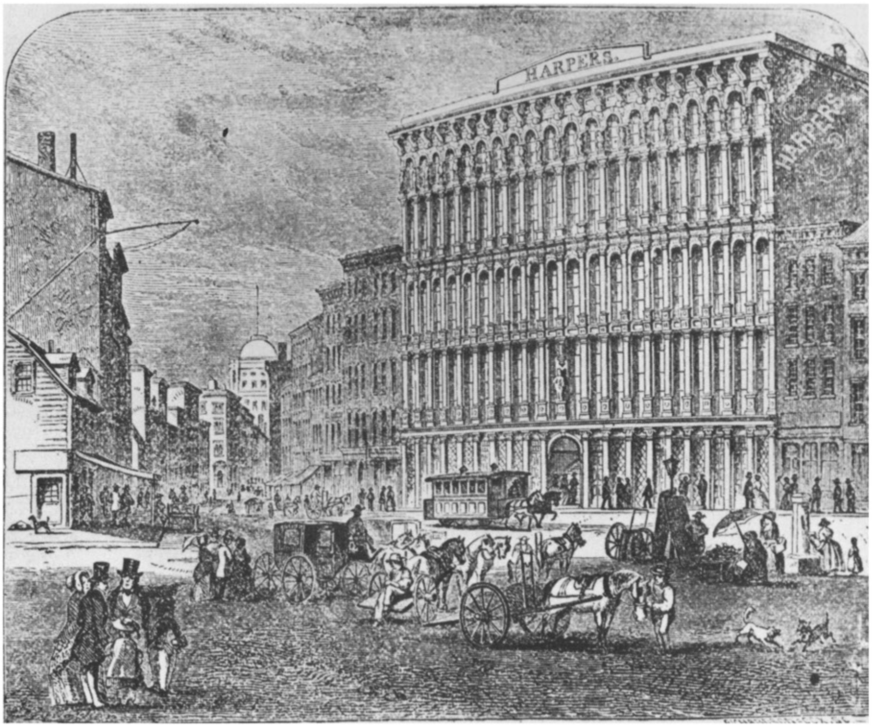
> apart, bolted together story upon story. The light castings, the arches, the soffits, the sill, the ornaments are all fitted in their place and bolted or secured fast. Lying on the floor the iron front is thus put together in all its parts. A surface of oxide of iron paint is given to the work. The parts are then separated, care being taken to mark each piece so that it can be put back in its proper place.[22]

By 1858, eleven years after his first building project, Bogardus's catalogs listed more than 30 projects, including five in Chicago and one each in San Francisco and Havana. The best known was the printing plant built for the publishing house of Harper Brothers after its previous building burned in 1853. The new building was designed by John B. Corlies, an architect and contractor (fig. 4.7). The upper four floors of its facade were cast in the molds used for the Baltimore Sun Building, but new designs, rather more ornate, were made for the ground-floor pieces. The interior framing was laid out by Corlies. Between columns ran decorated composite girders made of cast iron and wrought iron, and they in turn supported rolled wrought-iron beams in inverted T-shapes with an enlargement along the top edge. These beams were placed less than 3 feet apart, and their flanges carried shallow brick arches over which a concrete floor was poured.[23]

Bogardus was not alone in the development of cast-iron construction, and at the time that the Harper Brothers Building was under construction a San Francisco foundry advertised its own line of cast-iron storefronts. In fact, Daniel D. Badger had erected a cast-iron storefront in Boston six years before Bogardus's first effort. In 1846 Badger moved his foundry to New York, where he combined the fabrication of building elements with the manufacture of rolling metal shutters, a necessary protection for show windows before electric lighting permitted merchants' displays to be safely lighted all night. One of Badger's largest projects was E. V.

4.7 The use of cast iron for the facade of the Harper Brothers Building provided a simple, repetitive design that was also inexpensive. However, the low initial cost of cast-iron fronts was offset by the need for masonry backup and periodic repainting. (*History of Real Estate, Buildings and Architecture*, 1898.)

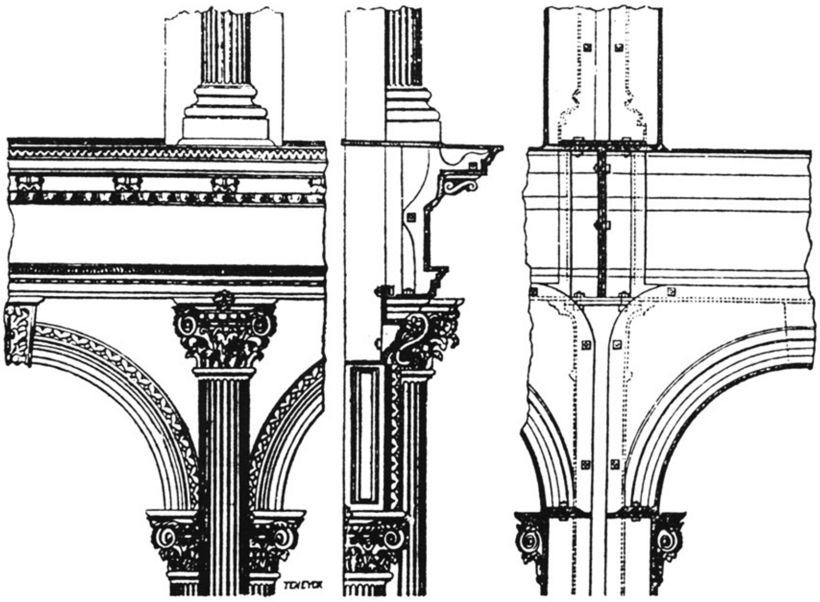
4.8 Front and back views of a portion of a Bogardus cast-iron storefront, with a section that indicates the manner in which the parts were bolted together. If spaces behind were not filled with masonry, they became dangerous ducts through which fire might spread. (J. Bogardus, *Cast Iron Buildings: Construction and Advantage*, 1858.)

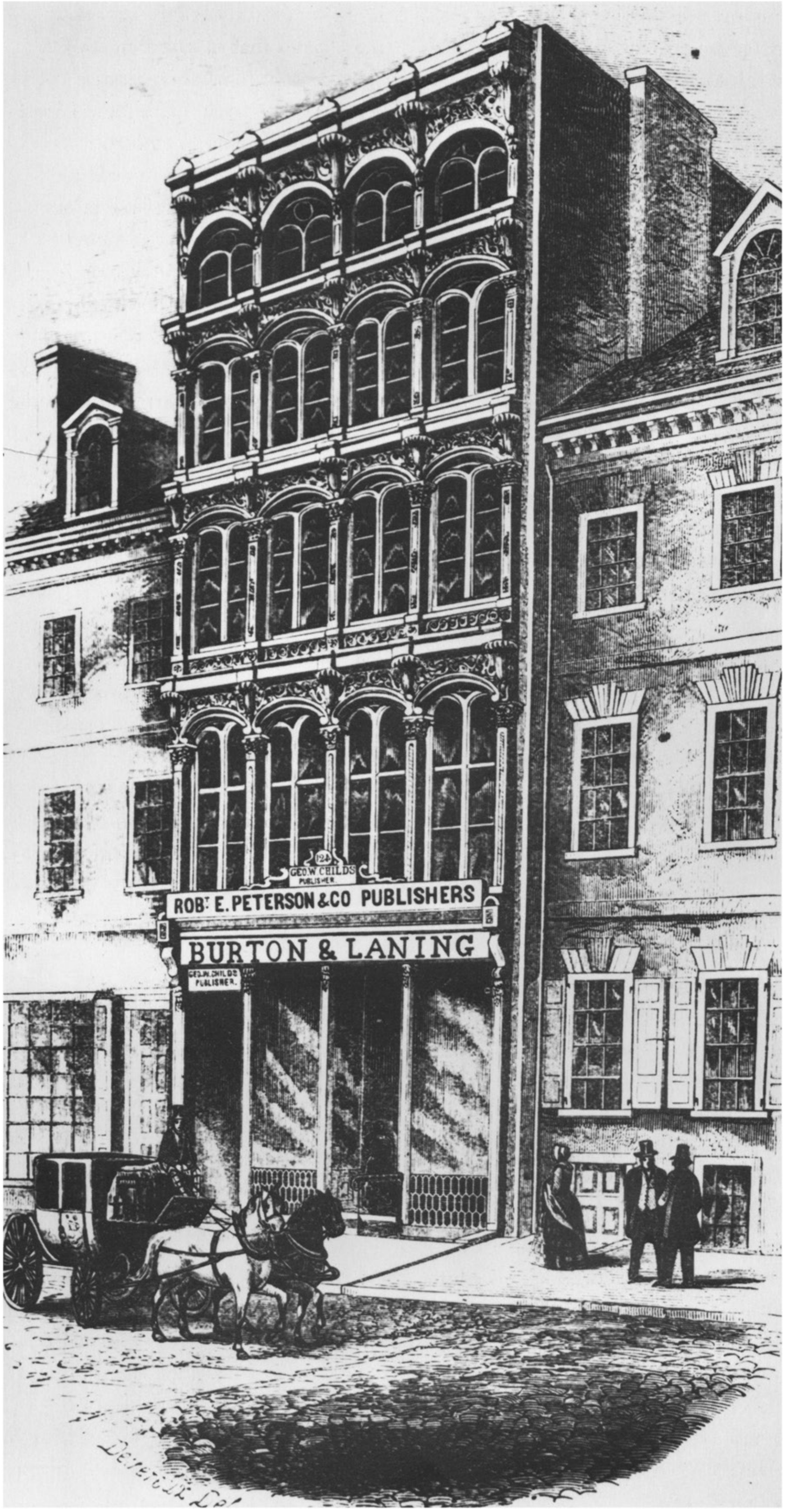


Haughwout and Company's store on Broadway, in which Elisha Graves Otis installed his first passenger elevator. In spite of the banking panic in 1857, the sale of cast-iron fronts boomed, perhaps because of the surge of westward migration. The Cornell Iron Works in 1859 supplied the facades for A. T. Stewart's store on Broadway, occupying an entire block, 200 feet by 328 feet and 85 feet high. John Kellum, architect for the store, employed cast-iron columns and wrought-iron girders on the interior, but the floors were framed with wooden beams. The building was completed in stages, and the rhythm of bays and arches varied in horizontal dimensions in the different phases of construction, a significant problem since repetition was the only identifiable basis for the design. The owner was said to have compared his structure to "puffs of white clouds," but others found little to favor in iron painted white and window shades of bright blue. One critic sneered: "When these shades are pulled down, the architect, if, indeed, it ever had one, must be congratulated upon having manufactured the most purely ugly and conspicuously offensive structure in New York City if not in the whole continent."[24] Nevertheless, Stewart's store was commercially successful, and a fourteen-story addition was built after it was bought in 1896 by the Philadelphia merchant John Wanamaker.

After the Boston fire of 1872, it was reported that fire had spread through cavities behind cast-iron facades, but since many such buildings had floors and roofs constructed with wooden beams, joists, and decking, this seemed only a secondary problem. Later fires further proved the need for blocking off the vacant space behind cast-iron panels, but it was 1885 before New York building regulations addressed the problem.[25] By the end of the century, many other U.S. cities had adopted legal requirements for filling behind cast-iron panels. In New York, brickwork 8 inches thick was demanded; wherever similarly stringent requirements were made, the iron castings might become merely facings for full masonry walls, losing their structural function and much of their economic advantage.

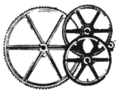
The cast-iron storefront was on the whole peculiar to the United States and was spurned by most European architects. When an English architect reported to colleagues in 1882 on his tour of cities in the northeastern United States, he observed that several cast-iron fronts had been built in London. His listeners were assured that "the passer-by certainly does not admire them, and only looks at them, if at all, as eccentricities of a peculiarly vulgar kind."[26] Cast-iron storefronts afforded large window areas, an important factor for retail sales establishments, but the inexpensive imitation of stonework was as strong a factor in their use. The need to paint the iron was often viewed as an opportunity for a new tenant to





4.9 *Gleason's Pictorial* in 1853 published this drawing of a "new iron building" erected in Philadelphia. Cast-iron fronts were popular for commercial structures of this sort, where masonry party walls could be combined with a front that provided large areas of windows and inexpensive architectural details. Glass-filled grillwork beneath the ground-floor display windows could provide light to the basement. (*Gleason's Pictorial*, 16 July 1853.)

employ a distinctive color, an advertising advantage that might well outweigh the cost of maintaining paint on the facade. Ten years after the English report, a writer in the United States put forward the notion that the decline of cast-iron fronts resulted from the fact that architects "let the cheapness of the material—cast iron—run away with their good sense," leading them to engage in frivolous ornamentation.



For the nineteenth-century builder, cast iron and wrought iron had complementary advantages and shortcomings. Cast iron was produced inexpensively and there were many local ironworks from which castings could be obtained. By casting in sand and other materials, it was possible to obtain structural members of a distinctive shape without incurring great expense, and architects could easily indulge their own decorative tendencies or duplicate traditional forms. As in firing ceramics, care had to be taken that the design did not require significant variations of thickness, which could cause a casting to warp as it cooled.

Cast-iron members were usually bolted together; a precise joint between the pieces could be obtained by planing and grinding the surfaces to be joined, an expensive procedure, or by using some plastic material as a grout between the surfaces. Nevertheless, the bolted connections were not always absolutely rigid. In fires, columns and beams of cast iron often cracked when chilled by water from firemen's hoses.

Although the usual nineteenth-century wrought iron had a compressive strength much less than that of cast iron, its tensile strength was about three times that of cast iron and almost equal to its compressive strength. Cast iron was a logical material for use as columns because its strength in compression permitted small columns to replace the large masonry piers that had occupied so much floor space. At the same time, its low strength in tension made cast iron less advantageous for beams. It is not surprising that the use of cast-iron columns continued, particularly in the United States, long after that material had been replaced by wrought iron for other portions of the structural framework.

Cast iron contains around 3 percent carbon, wrought iron usually less than 0.1 percent. The advantage of removing carbon from pig iron lies in the ease with which wrought iron can be shaped and its strength in tension. There was an ancient method by which wrought iron was made directly by melting ore and blowing air over the ore, thus providing oxygen for burning out the carbon. The process of converting pig iron to wrought iron involved several metallurgical problems. Iron smelted with coal or coke was much less costly than that smelted with charcoal, but both coal and coke iron contained deleterious substances. Coal-smelted iron contained sulphur, which caused it to be brittle; coke-smelted iron contained silicon. Melting the pig iron with coal eliminated most of the silicon, but added sulphur from the coal. At first the iron was placed in crucibles or "pots" with lime as flux to draw out the sulphur. In England the potting process, as it was called, produced about as many bars of malleable iron as were made with charcoal. A better method was found, but it did not begin to replace potting until around 1795.

4.10 The puddling process resulted in a ball of iron interlarded with molten slag, the latter removed by hammering or compacting the iron. The "crocodile squeezer," shown here, pressed the iron as it was gradually moved nearer to the fulcrum of the squeezer's upper jaw. (*Appleton's Cyclopedia*, 1880, 2:195.)

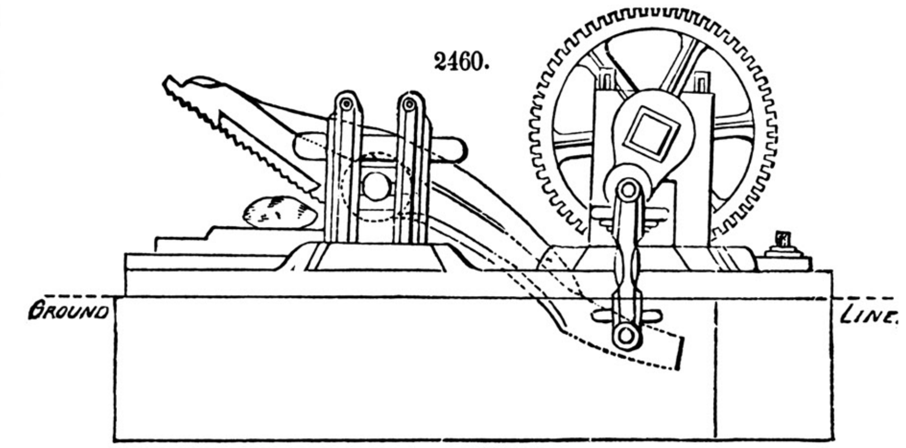
In 1784 Henry Cort, who had entered the iron business only nine years before, patented a process that allowed more efficient preparation of wrought iron, the method known as "puddling." A shallow tank was filled by melting pig iron or pouring molten iron from another furnace. Through the use of a reverberatory furnace, in which fuel was kept separate from the iron and heat was provided by flames drawn over the tank, the iron received no carbon from the fire. Once the iron was liquid, a "puddler" stirred it, allowing air to reach the carbon it contained. The purified metal had a higher melting point than the impurities in it, and therefore as they were stirred the two substances separated. The process has been compared to churning cream to make butter. One of the best descriptions was provided by James J. Davis, Secretary of Labor under Presidents Harding and Coolidge, who had been a puddler in his youth:

> My spoon weighs twenty-five pounds, my porridge is pasty iron, and the heat of my kitchen is so great that if my body was not hardened to it, the ordeal would drop me in my tracks.
>
> Little spikes of pure iron like frost spars glow white-hot and stick out of the churning slag. These must be stirred under at once; the long stream of flame from the grate plays over the puddle and the pure iron if lapped by these gases would be oxidized—burned up.
>
> Pasty masses of iron form at the bottom of the puddle. There they would stick and become chilled if they were not constantly stirred. The whole charge must be mixed and mixed as it steadily thickens so that it will be uniform throughout. I am like some frantic baker in the inferno kneading a batch of iron bread for the devil's breakfast.[27]

Taken from the furnace in balls usually weighing about 80 pounds, the iron was compacted by rollers or hammers that were driven by water or steam, forcing out the molten slag and shaping the wrought iron into bars (fig. 4.10).

The processes of puddling and rolling iron had appeared in other patents, but Cort's contribution was the combination of those procedures into an economical method of producing wrought iron. Unfortunately Cort gained nothing from his work. Needing financial assistance, he took a partner to whom he assigned his patent; when it was discovered that his partner's funds had been obtained by misappropriating government finances, the patent was useless.

Wrought iron could be rolled into plates or rods, and it was in these forms that it found its early uses. Plates were riveted to form boilers, and rods served as ties for masonry and for timber trusses. During the period from 1830 to 1850, many efforts were made to combine cast iron and wrought iron in a manner that would overcome the limitations of cast iron and exploit the characteristics of wrought iron. An 1847 study of the use of cast iron in railway bridges, surveying prominent engineers, found that on an average they considered the maximum feasible length of a cast-iron beam to be about 45 feet, with 60 feet the highest figure given by any of these experts.[28] To overcome this limitation, bridge engineers built up beams of cast-iron sections and added wrought-iron rods, bending them down to the bottom of the beam at the center of its span. This form, which attempted to combine the catenary of a suspension bridge with a simple beam, was generally unsuccessful when used for bridges and was seldom employed in building construction. In trusses the distinction between compressive functions and tensile elements was more clearly identifiable, and composite

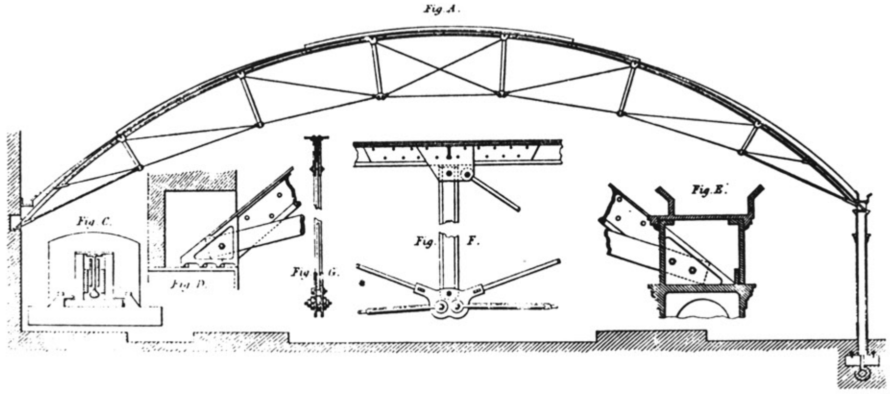


assemblies were more successful in such applications.

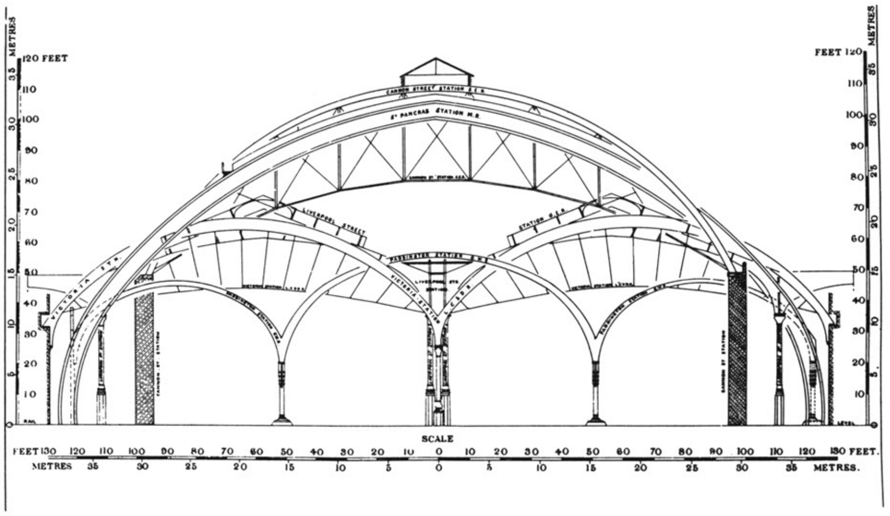
With the development of rolling mills, relatively efficient structural shapes could be fabricated, but they were limited in size. To attain a girder longer than the 60 feet that was a maximum in cast iron, it was necessary to use riveting techniques that had been developed by boilermakers and shipbuilders. Girders could be made up of plates, angles, and Z-bars, but the cost of such work was high. By the time that wrought-iron beams deeper than 7 or 8 inches were available, steel could be had.

* * *

An English advertisement in 1832 pictured a warehouse built in the vicinity of the London docks and extolled the merits of the material of which it was made, "Patent Corrugated Iron" as marketed by the firm of Richard Walker. The warehouse, over 200 feet in length, was covered by a vault of fluted metal that spanned 40 feet between two U-shaped cast-iron beams, which also served as gutters.[29] Previous structures of a strictly utilitarian purpose had been vaulted with iron sheets cast with rectangular ridges to stiffen them. Walker's material was wrought iron, produced in larger quantities with a new method by which the material was rolled into sheets instead of being formed by hammering. The first corrugated sheets were formed by a laborious process that made only one furrow at a time, requiring much labor and extreme precision for a workman to complete a sheet of corrugations satisfactorily. In 1844 a British patent introduced a machine that would form corrugations by passing flat sheets between rollers that were fluted longitudinally. If an arched sheet of corrugated metal were desired, the sheet could then be passed through a machine with three rollers that had ridges around them. Later patents further developed the method of rolling corrugations and added machinery for shaping corrugations by means of



4.11 In the trusses of the Lime Street Station, Liverpool (1848–1849), straps along the lower edge of the crescent were intended to restrain the truss and avoid outward movement of its ends. However, the length of those straps would vary with temperature, and the trusses were set on rollers at one end (*D*). Later, after it was observed that rust and paint on the rollers of bridges indicated that they had not moved, some engineers often questioned their usefulness. (*Transactions, Newcomen Society*, 1964–1965.)

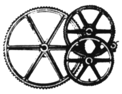


4.12 The spans of five major English train sheds are here superimposed for comparison. This composite diagram can be compared with the diagrams of figure 4.13. (A. T. Walmisley, *Iron Roofs*, 1888.)

dies, usually stamping only a few ridges and furrows at a time in order to avoid stretching the sheet.[30]

Iron sheets were subject to rust and weathering, especially damaging because of the metal's thinness, and tin was the first material used to provide a protective coating. In the sixteenth century the Germans beat iron into sheets with mechanized hammers and, after cleaning the surface, dipped the sheets in melted tin. By the middle of the eighteenth century a finer quality of sheet iron for tinning was provided by the rolling process. In early French experiments it was discovered that coatings of zinc produced a hard protective covering that bonded well to the iron beneath. Little was done with this knowledge until the French chemist Ernest Sorel rediscovered that process in his experimentation to find ways of protecting sheet metal from rust, an important investigation if metal were to be used for sheathing the hulls of ships. Sorel's patent of 1837 outlined a process of dipping cleaned sheets of iron into molten zinc, which was protected from vaporization by having a layer of sal ammoniac or resin floating on top.[31] It was Sorel who introduced the term "galvanize," apparently convinced that the bond between the iron and zinc was the result of some form of electrolytic or galvanic action.

In the construction of prefabricated structures, an appropriate concern because of colonial expansion around the world, the simplicity of iron frameworks had been contradicted by the necessity of applying traditional roofing materials. Iron sheet roofing, corrugated to lesson the weight required and galvanized to protect it from weather, answered both the problems of shipping the structures economically and of maintaining them in the colonies. Its use increased as droves of adventurers responded to the lure of gold, discovered in California in 1849 and in Australia two years later. Other ores and further colonization caused the development of a vast market for corrugated metal, for in the vicinity of riches few cared to engage in carpentry. Warehouses and gold rush construction found the use of corrugated iron to be eminently sensible. For the most part, the material remained restricted to use in coarse utilitarian buildings, but in New York and other cities corrugated iron often covered the roofs of major buildings—though hidden by the parapets and cornices.

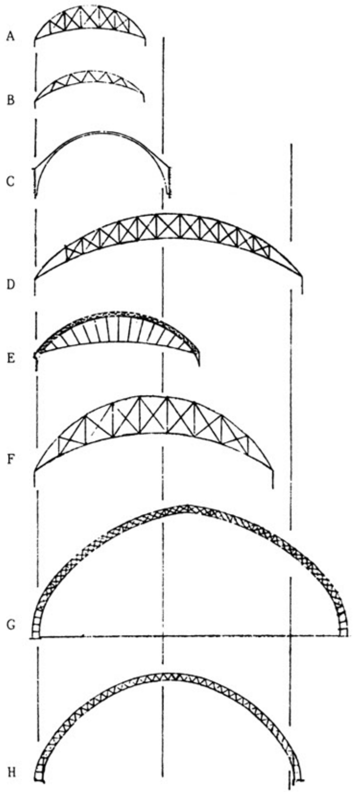


For the Great Exhibition of 1851, the Crystal Palace was erected in London's Hyde Park, and two years before Lime Street railway station had been completed in Liverpool. There were other kinds of buildings with roofs of metal trusses, but few have matched the prideful display of structure to be seen at expositions and railway stations in the late nineteenth century. Lime Street station spanned a train shed 154 feet wide with crescent-shaped trusses, at that time one of the most popular types, particularly in England and Germany (fig. 4.11). The top lines of the crescents and the trusses' vertical members were shaped for compression, the bottom lines were made of flat iron bars, and diagonals were usually round rods.[32] The roof of Lime Street Station was covered with rough glass and sheets of metal, corrugated and galvanized. A greater span, 211 feet, was achieved a few years later in New Street Station, Birmingham. Lime Street Station had only one diagonal rod in each panel of the truss, but New Street Station had diagonals in both directions, a design that better provided for the horizontal forces of wind.[33]

Another early system of roofing train sheds was an arched truss in which the curve of the roof was followed by triangulated lattice work. Because this form of truss did not have a tension rod along its bottom line, it was necessary to compensate for outward pressures at the bases of the truss. In the Gare de l'Est, Paris, built in 1852 with the modest span of 100 feet, a network of rods filled the curve, serving as a bowstring between the ends of the trusses. In Victoria Station in London, rods from each vertical member of the trusses supported the shallow upward curves of the bowstrings that connected the heads of columns on which trusses rested. Such provisions against outward thrust were eliminated in the design of the train shed for St. Pancras station, London, built in 1866 (figs. 4.14, 4.15). There the trusses, spanning 240 feet, took the form of a slightly pointed arch. Instead of resting the trusses on columns or walls, their curvature was extended to the floor, thereby providing resistance to the outward thrusts of the arch. The arches of St. Pancras were much like those that had been used a few years before to provide a roof spanning 108 feet over the furnaces of a Berlin gasworks, except that the German structure used pivoting pin connections at the base of its arches and St. Pancras had a rigid connection at that point.[34] (The Berlin gasworks may have been the first to use pin connections to provide for the flexing of arches under wind pressure and temperature changes.) St. Pancras was expensive in initial cost, and the chairman of the Midland Railway Company said that, "although the proprietors were proud of it as a triumph of engineering skill, it was an utter abomination as a railway station from an economical point of view."[35] Nevertheless, similar train sheds continued to be built. The 1870 Grand Central Station in New York was similar in structure, although less elegantly formed and shorter in span.

The Hauptbahnhof at Frankfurt-am-Main, built from 1879 to 1888, replaced three separated railway stations with a single building combining three arched train sheds, each having a span of 183 feet. This was the introduction of the three-hinged arch, which employs a pivoting connection at each base and at the crown of the roof. This improvement isolated each of the pieces that made up the truss from transfer of the complex forces that resulted from wind or temperature changes, and thus it greatly simplified structural design of the roofing system. The largest train shed of this type was the Broad Street Station in Philadelphia, which had a span slightly greater than 300 feet.

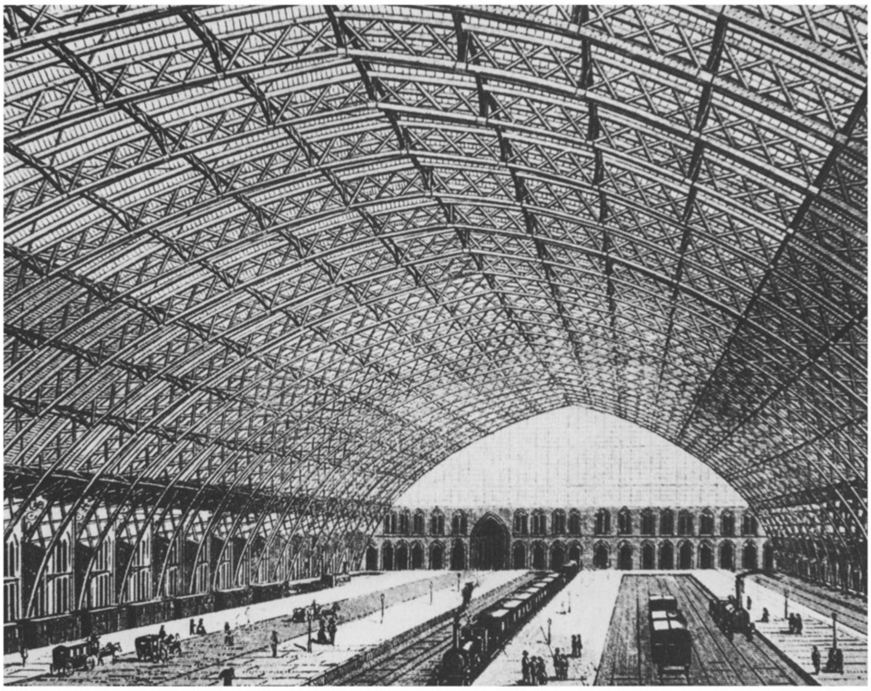
Early in the twentieth century, interest in long-span train sheds



4.13 Eight nineteenth-century British train sheds in chronological order. Spacing of the vertical lines measures 100 feet. (*A*) London Bridge Station, London; (*B*) Lime Street Station, Liverpool; (*C*) King's Cross Station, London; (*D*) New Street Station, Birmingham; (*E*) Victoria Station, London; (*F*) Cannon Street Station, London; (*G*) St. Pancras Station, London; (*H*) St. Enoch's Station, Glasgow. (Drawing adapted from *Builder*, 22 September 1906.)

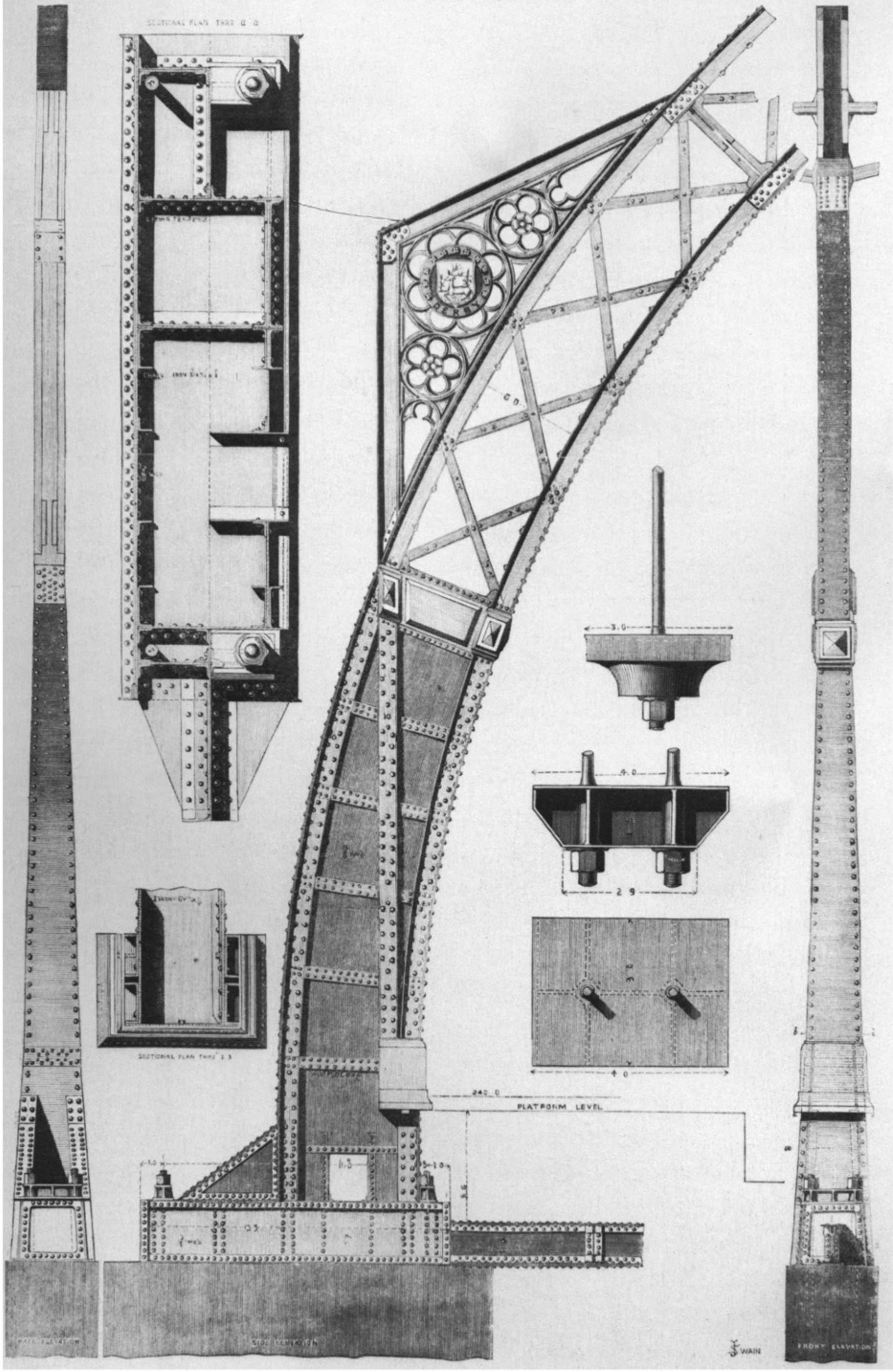
4.14 In St. Pancras Station (London, 1866), iron arches spanned 240 feet, a distance that was long unequaled. The pointed arch was believed to offer advantages in the structure's resisting wind pressure. (*Iconographic Encyclopedia*, 1889, vol. 5.)

4.15 The arches of St. Pancras Station extended to ground level where a rigid connection was made, instead of the rollers, pivots, or rockers that were often used for long-span construction. The vertical member that crosses the arch establishes the location of walls for service facilities along the side of the train shed. (*Engineer*, 7 June 1867.)



MIDLAND RAILWAY EXTENSION—ST. PANCRAS STATION—DETAILS OF MAIN GIRDERS.

MR. W. H. BARLOW, C.E., F.R.S., ENGINEER.



4.16 After the Great Exhibition closed, the Crystal Palace was dismantled and moved from London's Hyde Park to a suburban site, where it was reassembled. Pools, plants, and fountains were installed for the pleasure of paying visitors. (*Iconographic Encyclopedia*, 1889, vol. 5.)

4.17 The Crystal Palace and the Great Exhibition it housed were a success by several prime criteria of the Victorian age. The building was inexpensive, costing two-thirds the estimated price of a brick building; it was completed quickly; and the exhibition made a profit. Prefabricated and standardized construction of iron and glass made these successes possible, but the large arches of the roof (background of this drawing) had to be made of wood. (*London Illustrated News*, 16 November 1850.)

waned. A British engineer explained in 1906,

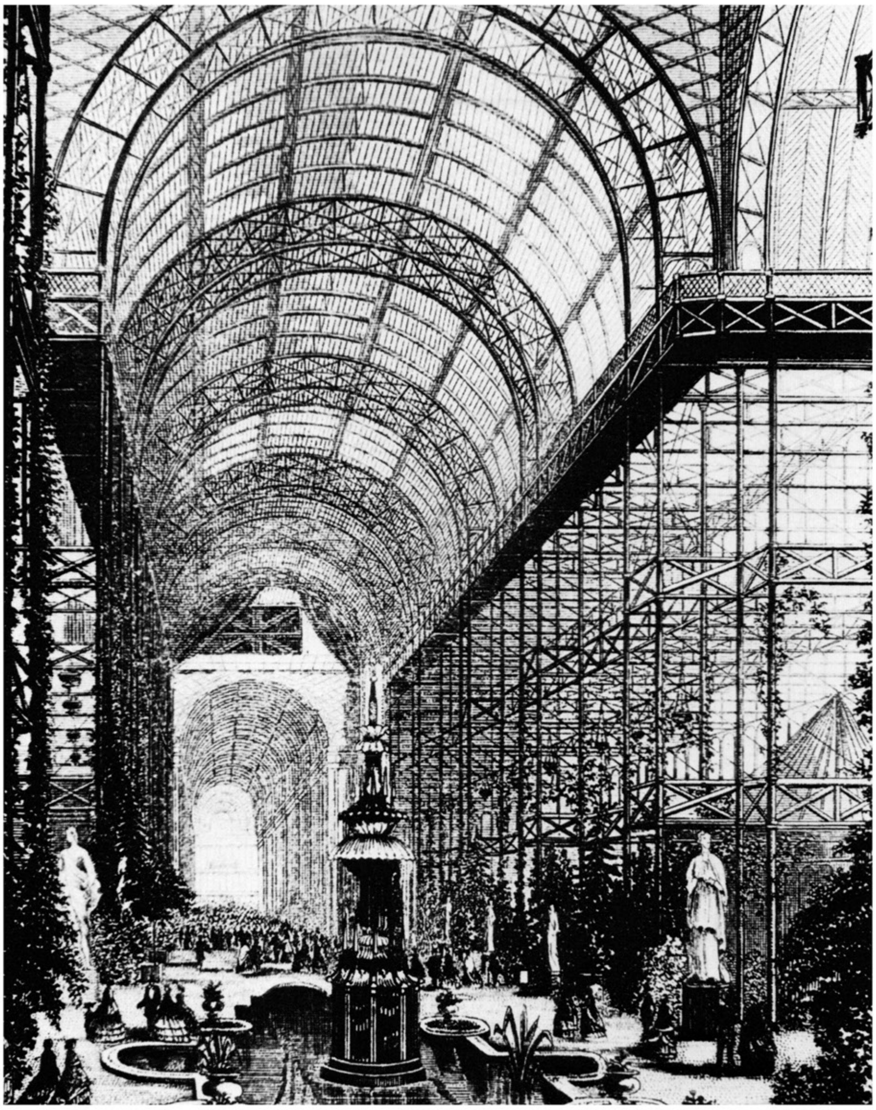
> In justice to the designers of railway station roofs, it must be pointed out that the fashion for ostentatious spans did not originate with them, but with traffic managers, who thought it desirable that the whole interior area should be absolutely unimpeded by columns or interior supports. Fifty years of experience have served to dispel this notion, and we are now on the point of returning to the least ambitious ideal which possessed engineers in the early days of the railway system.[36]

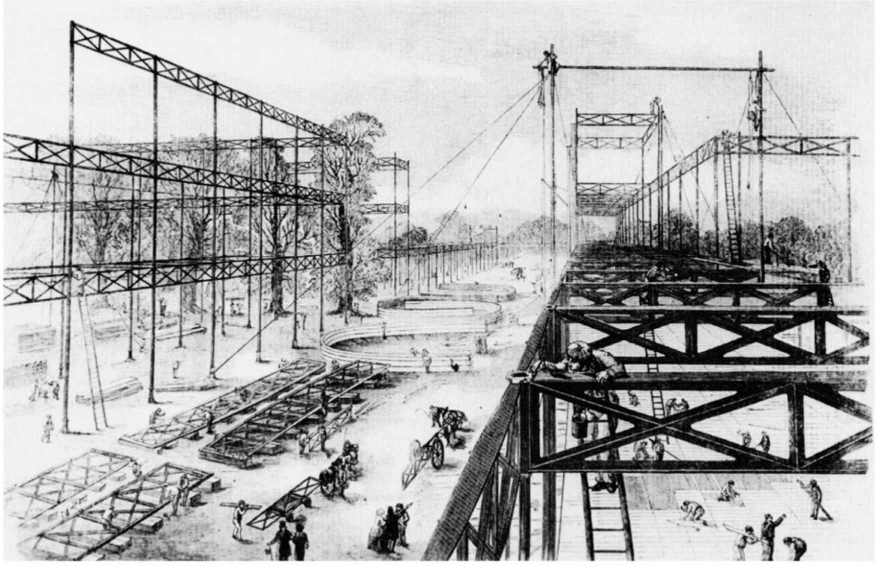
After half a century invested in the competitive construction of broad spans, railroad stations began to be made of repeated small spans, usually around 50 feet and seldom over 150 feet.

The rapid acceptance of iron construction demanded that there be speedy advances in theoretical knowledge and practical experience. During the 1840s, the railway mania in England had required that bridges be built quickly, and the knowledge that was gained from those successes and failures contributed to the understanding of the structural requirements of long-span construction in buildings. The most famous bridge engineers occasionally designed arches and trusses for buildings, but most of the latter were the work of young men of practicality who received their training during the flurry of construction activity. For instance, Rowland Mason Ordish began as a draftsman in the London office of an engineer who was engaged principally in designing bridges. After Joseph Paxton's first sketches were accepted for the building of the Great Exhibition, the Birmingham engineers Fox, Henderson and Company undertook calculations and the preparation of detailed drawings that were necessary to translate Paxton's ideas into a building. Ordish participated in this work, and he played a larger role in the reassembly of the Crystal Palace when it was moved to Sydenham. While with the firm of Fox and Henderson, Ordish prepared construction drawings for the New Street railway station in Birmingham, the longest span of the time.

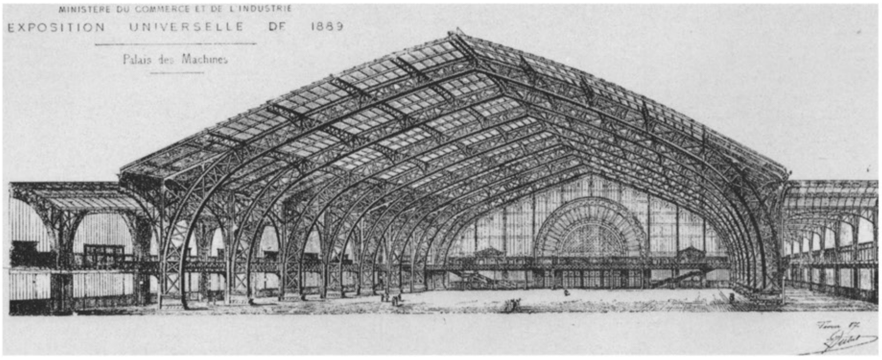
In his own engineering practice Ordish later prepared designs for a series of bridges, exhibition structures, and train sheds that include a surprising number of the period's significant metal constructions. Either in developing architects' designs or as a consultant engineer, Ordish contributed to a series of projects that included winter gardens (including that of the Dublin Exhibition in 1865), many bridges, the dome of Royal Albert Hall, and railway stations in Amsterdam, Glasgow, and London.[37] The roof for St. Pancras station was designed by Ordish in collaboration with the railway company's engineer, and around 1870 Ordish acted as engineer for a cast-iron kiosk to be erected in India, the design by Owen Jones. When there was concern about the stability of the vaulting over the octagonal chapter house at Westminster Abbey, Ordish added an iron roof framework from which the medieval vaulting was suspended.

In almost every country there were practical men of this sort—builders, engineers, ironmakers—who developed great skill through experience in metal construction and who acquired a degree of theoretical knowledge. When the rapid growth of iron construction began, there were no experts. Theoretical explanations of trusses and arches were subject to many divergent opinions, and often the practical men, learning from experience, were the source of the most reliable information. On the whole, they were not unaware of mathematical theories as they were developed,

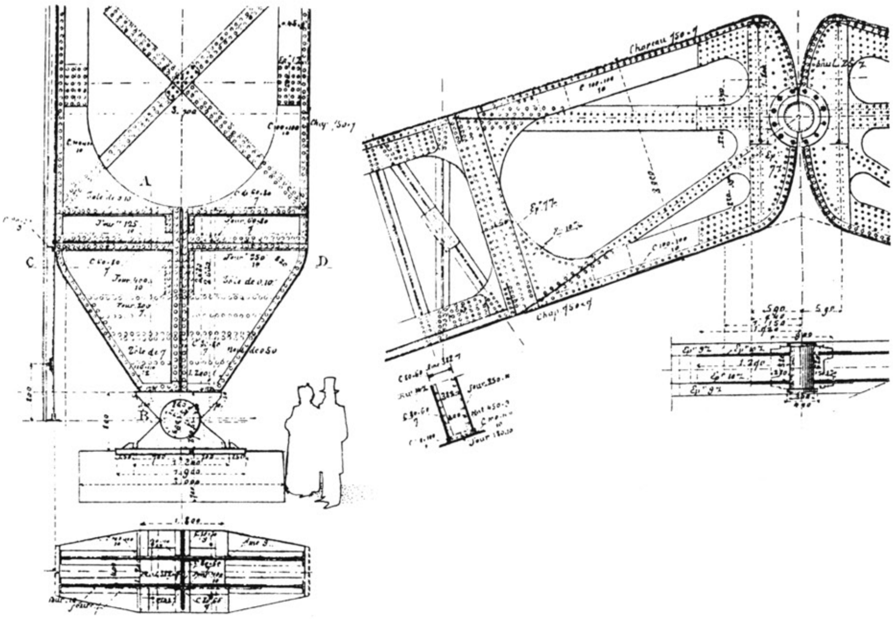




4.18 **The Galerie des Machines of the 1889 Exposition in Paris was the largest span built since St. Pancras Station over two decades before. This drawing, which was published in 1887, does not indicate the pin connections of a three-hinged arch, but its publication was accompanied by details showing pin connections (fig. 4.19). (*Construction Moderne*, 6 August 1887.)**



4.19 **Details of the three-hinged arches used in the Galerie des Machines demonstrate the vast number of rivets used to form them of wrought-iron sheets and angles. The arches were actually constructed like box girders with about 16 inches inside between the two faces. (Human figures have been added to the drawing to suggest the scale of the structure.) (*Construction Moderne*, 6 August 1887.)**



but the practical man's decisions were firmly guided by the experience gained in constructing railways, bridges, railway stations, and the spectacular iron-and-glass exhibition buildings that were monuments to the technological advances of the last half of the nineteenth century.

The Crystal Palace suffered from an excessive amount of light, requiring shades in some areas and tentlike shelters for certain exhibits (figs. 4.16, 4.17). The two exhibitions that followed (Dublin, 1853; New York, 1853–1854) avoided this problem by limiting glass areas to clerestories and sidewalls. Both were built much like the Crystal Palace, iron lattice girders and arches providing most of the structural framework. At Dublin, as in the Crystal Palace, laminated wood was used for the arches having the longest spans. The Palais de l'Industrie, principal building of the Paris Exposition Universelle in 1855, used a similar central vault with flanking galleries. About one-third of its central roof was glass, and inadequate ventilation often caused sweltering heat in the exhibition areas. All of this was wrapped in a stone wall, three stories high and detailed in the accepted academic style. Seven years later the London International Exhibition had a similar surround of masonry, resulting in a building disliked by both traditionalist architects and progressive engineers.

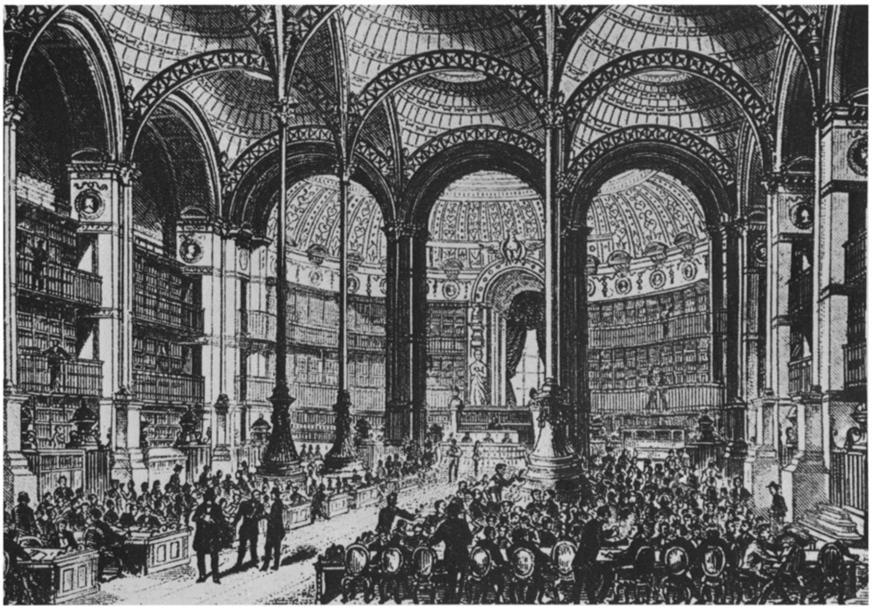
The plan of the 1867 Exposition Building in Paris was based on a system for classifying exhibits, but the circular principle of organization was converted to an ellipse in order to fit within the limits of the site. Only the next to last ring, the Galerie des Machines, required a significant span, over 111 feet, and it was much higher than the rest of the building. Instead of using the customary methods of resisting outward thrusts of the arches, the columns were extended as high as the crown of the arches and connected with tie rods. One engineer later evaluated the system as "an expedient and on the whole an expedient of little rationality since the tie rods placed above do not really relieve the foundations, they must resist the same horizontal pressure, just as though the tie rods did not exist."[38]

Between 1867 and 1900 there were thirty-three international fairs held, averaging one per year. The sites varied from 3 acres (Kimberley, South Africa, 1893) to 685 acres (Chicago, 1893); attendance ranged from less than a quarter-million (Brisbane, Australia, 1897) to over 32 million (Paris, 1889). Of these, the Expositions Universelles held at Paris in 1878 and 1889 mark major advances in the development of long-span construction in France. The earlier of the two exhibitions had a Galerie des Machines that was over 2,000 feet long with structural elements of 107-foot span, spaced about 50 feet apart. The latticework of those ribs ran between the slopes of the gable roof and a bottom curve in the shape of a pointed arch. The deep haunches provided by this shape stiffened the arch against the lateral pressure of winds, and such arches did not require tie rods or buttresses. Around a decade before, this form had been used in England for St. Pancras Station and in Germany for the Palmen-Garten in Frankfort. In France it was unusual: "From the point of view of construction, it is a novelty; from the point of view of stability, a tour de force."[39]

162The system was further developed in the Galerie des Machines at the Paris Exposition of 1889, a building so large and powerful that it could compete against the Eiffel Tower for the public's attention (figs. 4.18, 4.19). Its length was more than a quarter-mile and the three-hinged arches spanned

375 feet. At the top and both feet of each arch, steel rollers were installed, 14 and 20 inches in diameter. Steel had been considered for construction of the arches, but for economy wrought iron was used instead.[40] The space was so vast that above the displays of engines and machines an overhead platform rolled the length of the hall carrying visitors past the exhibits.

Visible ironwork might be acceptable for train sheds and temporary exhibitions buildings—particularly when the displays were machinery—but there was great reluctance to reveal iron structure in other kinds of buildings. The Bibliothèque Ste.-Geneviève in Paris, built in the 1840s, provided one of the first instances in which an iron structure was made visible in a building of dignity and permanence. In the library's reading room the architect, Henri Labrouste, placed a row of slender iron columns down the center of the long rectangular space. The semicylindrical vaults that spanned between the row of columns and the outside walls rose from iron arches of ornamental openwork. These vaults were simply plaster filled between the outer curves of the



4.20 The reading room that was added to the Bibliothèque Nationale (Labrouste, Paris, 1862–1868) had no facade, for it was fitted among other buildings of the library. Because of this restriction, toplighting was necessary, and the solution was nine domical forms, each with an oculus. Above the domes, a gabled roof protected the reading room. (*Iconographic Encyclopedia*, 1889, vol. 5.)

arches, and the gabled roof over both vaults was supported by vertical iron members placed at the quarter points of the iron arches. This was not a solution offering structural innovation, but it did much to introduce the decorative potential of structural ironwork.

The reading room of the Bibliothèque Nationale in Paris, built over a decade later, offered a clearer statement of Labrouste's use of metal construction (fig. 4.20). A square space, the reading room was covered with nine domical shapes, equal in size. A gabled roof was again supported by verticals from the iron arches that held the domes. Around the outside of the room, iron columns stood free of the masonry walls, allowing the metal structure to expand independently. At the end of the century, Auguste Choisy ended his classic *Histoire de l'architecture* with a paragraph on the Bibliothèque Nationale:

> In a masonry shell, which shelters the interior from changes of temperature, there is placed an iron framework in which the connections to the shell allow the metal's free expansion; and on this framework is supported an iron skeleton that carries three rows of three domes with enamel decoration. Not only in the forms but in the effects of color it is apparent that a new system of proportions is dawning, in which the laws of harmony will be none other than the laws of stability.[41]

* * *

Steel is an alloy of iron and carbon, but this fact was long unrecognized. In the making of metals, carbon was inescapably present in the fuel by which ores were melted, but only in iron and steel did its presence play a role so vital in determining the properties of the material that was produced. At the smelter's workplace various forms of carbon were everywhere, and it is understandable that this ubiquitous substance would not be quickly identified as the critical ingredient of the process. Through much of the eighteenth century, metallurgical thought was based on the phlogiston theory, which hypothesized the existence of a substance that embodied the qualities of fire. Since steel was made with great quantities of heat, it was long believed that phlogiston was a major factor in determining its character. The part oxygen played in combustion was discovered in the 1770s, and in 1781 Tobern Bergman, a Swedish analytical chemist, published the results of 273 tests on iron and steel.[42] Although Bergman clung to the phlogiston theory, he identified the quantities of plumbago (carbon) in cast iron, wrought iron, and steel, and so realized the importance of these proportions. Several years later a French chemist was able to write that "the conversion of iron to steel operates principally because either there is formed in it or it receives [from outside] an appreciable amount of plumbago."[43]

Chemical analysis did much to govern smelting practice and permit the preparation of metals from different ores. The fervor of the Industrial Revolution and colonial expansion assured rapid communication between scientists and ironmakers, but it was almost a century before microscopic analysis opened the next phase in understanding the nature of iron and steel.

A common early process for making steel involved three steps in which the chemical constituents of iron, especially carbon, were altered. First, cast iron was produced, having a relatively high percentage of carbon, between 2 and 4.5. This was melted

4.21 Bessemer's converter, as shown in U.S. Patent no. 16,082 (11 November 1856), corresponds to that in British Patent no. 356 (12 February 1856). At the lower left the converter is positioned for molten pig iron to be poured in; the upper left shows the position at which air was blown through valves at the bottom of the converter; and at the lower right the steel can be poured out.

4.22 Kelly's U.S. Patent no. 17,628 (23 June 1857) shows a converter drawn more crudely than that in the Bessemer patent. However, there remain the essentials: a place to pour in iron (*B*), openings through which air can be injected (C), and another out of which the finished steel may drain (*D*).

and stirred to burn out the carbon, producing wrought iron, which usually contained less than 0.1 percent carbon. The wrought iron was then melted and carbon added to produce steel, which had less than 1.7 percent carbon. Large quantities of fuel were required to complete this process and therefore steel demanded a high price and was used sparingly, usually only where a hard cutting edge was required.

During the Crimean War, Henry Bessemer invented a projectile that would rotate when fired from smoothbore ordnance. Trials conducted by the French government showed that the cast-iron barrels of guns were unable to fire the heavy projectile safely, and Bessemer thereupon launched his study of metal production. In 1856 he presented his findings to the British Association for the Advancement of Science in a paper deceptively titled "On the Manufacture of Iron and Steel without the Use of Fuel." In the patent he had taken out the previous year, Bessemer described his "converter," which he proposed as a fast and economical method of making steel (fig. 4.21). In an 1860 patent, the Bessemer converter consisted of a large container mounted on pivots. It was tilted to be filled with molten pig iron. Then it was moved to an upright position, and a blast of air was blown upward through the iron. Bessemer described this stage of the process: "A succession of mild explosions, throwing molten slags and splashes of metal high up into the air, the apparatus became a veritable volcano in a state of active eruption."[44] When sufficient carbon had been burned out of the iron, the converter was tilted once more to pour out its contents.

Major English ironmakers hurried to obtain licenses permitting them to use the Bessemer process, but time after time their trials were unsatisfactory. Perhaps the explosions that Bessemer had witnessed might have been stopped at a point when a correct amount of carbon remained in the metal, but in practical terms such precise control of a rather violent event was out of the question. The inventor had contemplated adding a measured amount of carbon at the end of the process, but that did not solve the problem. It was found that the iron melted in Bessemer's own experiments had been unusual in containing very little phosphorus; but licensees used their own iron which carried more phosphorus. Also, in the process the iron gained an excessive amount of oxygen.

These two chemical characteristics of the Bessemer process caused its output to be useless, until Robert Forester Mushet introduced into the process a compound that was patented in 1856. Mushet's *spiegeleisen* was a combination of iron, carbon, and manganese. When this compound was added molten to the iron, the manganese drew out oxygen and the carbon content was increased. Mushet, a reclusive and rather quarrelsome metallurgist, is said to have written, "Bessemer metal without Mushet = Iron; Bessemer metal with Mushet = Steel," and his statement was accurate.[45] The problem of phosphorus remained. Some English ironmakers obtained iron having a sufficiently small amount of phosphorus, and Swedish iron, recognized then as the purest, caused no difficulty. But most iron contained phosphorus, including that of France, Germany, Belgium, and the United States.

Although it was not realized at the time, phosphorus was retained in the iron because the Bessemer converters were usually lined with materials that

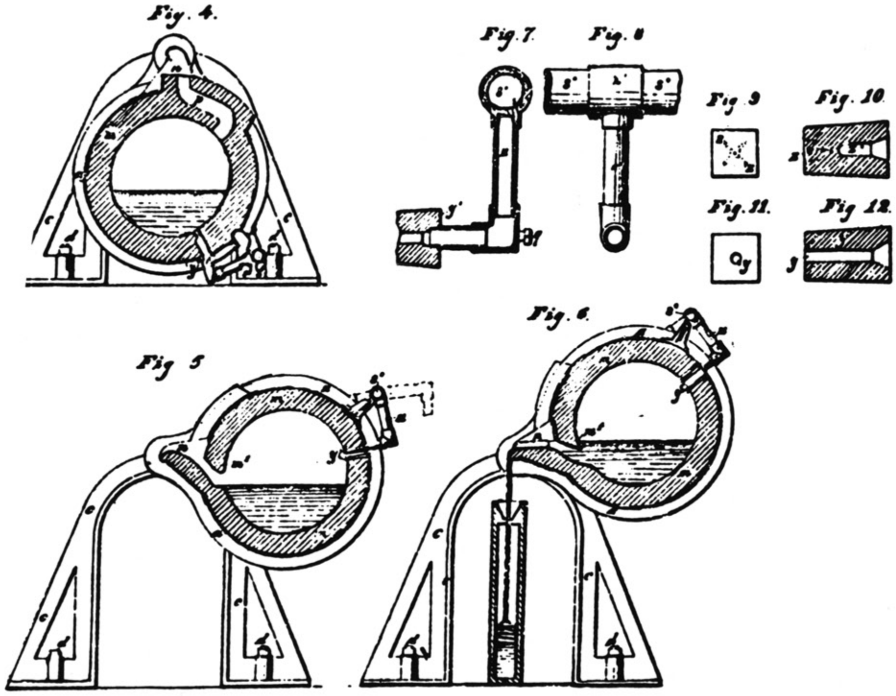


Fig. 4.

Fig. 7.

Fig. 8

Fig. 9

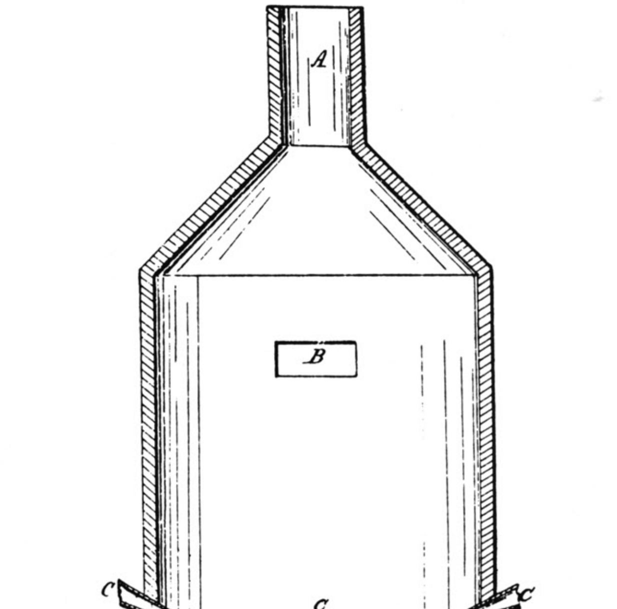
Fig. 10.

Fig. 11.

Fig. 12.

Fig. 5

Fig. 6.



4.23 Much of the mass of an open-hearth furnace consisted of tunnels in which fresh air passed through red-hot grilles of brick, which had been previously heated by escaping gases. A damper (C) switched the tunnel functions. The metal was melted on a sand bed (*T*) laid in an iron box, which had cooling air passages beneath to prevent its being burned out by the heat of the process. Compare this furnace with that used in glassmaking (fig. 5.15). (*Appleton's Cyclopedia*, 1880, 2:807.)

were chemically acid. In 1879, at the age of 29, Sidney Gilchrist Thomas, a clerk in a police court, and his cousin Percy Gilchrist, a chemist, discovered that base (alkaline) materials when used as a lining for converters could remove phosphorus from the iron. Only then, over 20 years after Mushet's introduction of *spiegeleisen*, did the Bessemer process—or more truly, the Bessemer-Mushet-Thomas-Gilchrist process—produce reliable steel. The Bessemer process was still restricted to using low-phosphorus (0.1 percent or less) iron if the converter were acid-lined; and to high-phosphorus (1.5 percent or more) if base-lined. This eliminated the use of the many irons with an amount of phosphorus that fell between those figures. By this time the open-hearth process, which did not rely on the material as a source of heat, could utilize iron of any phosphorus content.[46]

Bessemer's first British patent for making steel by forcing air through molten iron was dated 17 October 1855; his tilting converter received a British patent on 12 February 1856; and a more developed form of the converter received its British patent on 1 March 1860. A U.S. patent matching the second British patent was dated 11 November 1856.[47] These dates are significant because at the end of 1856 William Kelly, an American, instituted interference proceedings and claimed his own invention of the process had been prior to that of Bessemer. Bessemer's address to the British Association had taken place in August 1856 and was published in *Scientific American* on 13 September 1856. On 30 September 1856 Kelly had written *Scientific American* describing his own experiments. Hearings were held, and in April 1857 the Acting Commissioner of Patents decided that Kelly's invention had preceded Bessemer's and instructed that the U.S. patent be issued to Kelly if Bessemer did not appeal the decision within 60 days. No appeal was made.

Kelly had briefly studied metallurgy at what is now the University of Pittsburgh, and in 1846, when he was 35 years old, he and his brother bought the Eddyville Furnace in Kentucky. In the following year William Kelly began experiments on his "Air-Boiling Furnace" (fig. 4.22). As Kelly described it: "I conceived the idea that, after the metal was melted, the use of fuel would be unnecessary—that the heat generated by the union of the oxygen of the air with the carbon of the metal would be sufficient to accomplish the refining and decarbonizing of the iron."[48] The test of his first furnace was delayed for several years by the company's construction of a new blast furnace. In 1851 experiments were resumed:

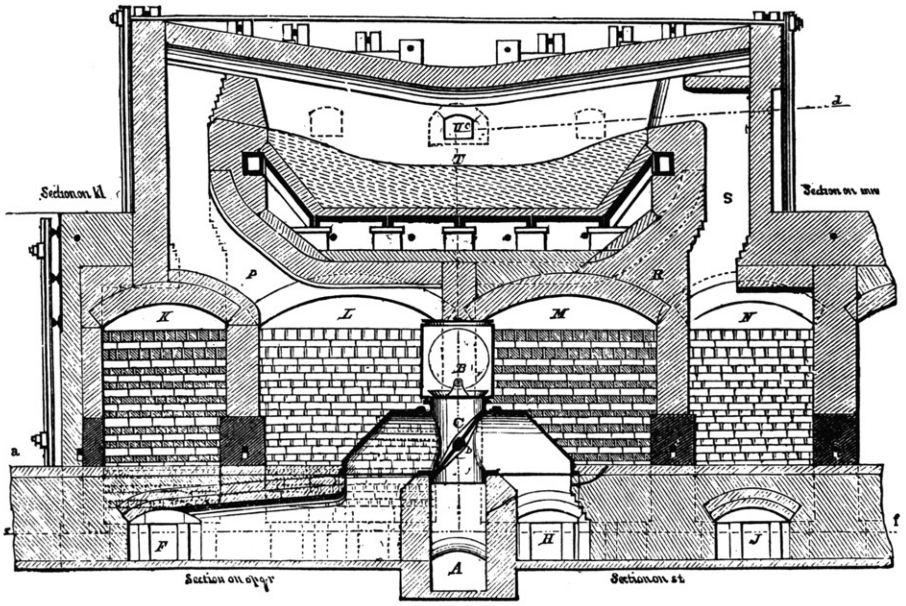
> On looking for the cause of failure in my experimental furnace, [I] found that my chief trouble lay in the melting department, not in the important matter of blowing into the iron, so that the question presented itself to my mind, Why complicate my experiments by trying to make pig metal in a furnace not at all suited to the business? Why not abandon altogether the melting department and try my experiments at our new blast furnace, where I could have the metal already melted and in good condition for blowing into? I fully believed that I could make malleable iron by this process. In my first efforts with this object in view I built a furnace consisting of a square brick abutment, having a circular chamber inside, the bottom of which was concave like a moulders' ladle. In the bottom was fixed a circular tile of fire-clay, perforated for tuyeres [air inlets]. Under this tile was an air-chamber, connected by pipes with the blowing engine. This is substantially the plan now used in the Bessemer converter.
>
> The first trial of this furnace was very satisfactory. The iron was well refined and

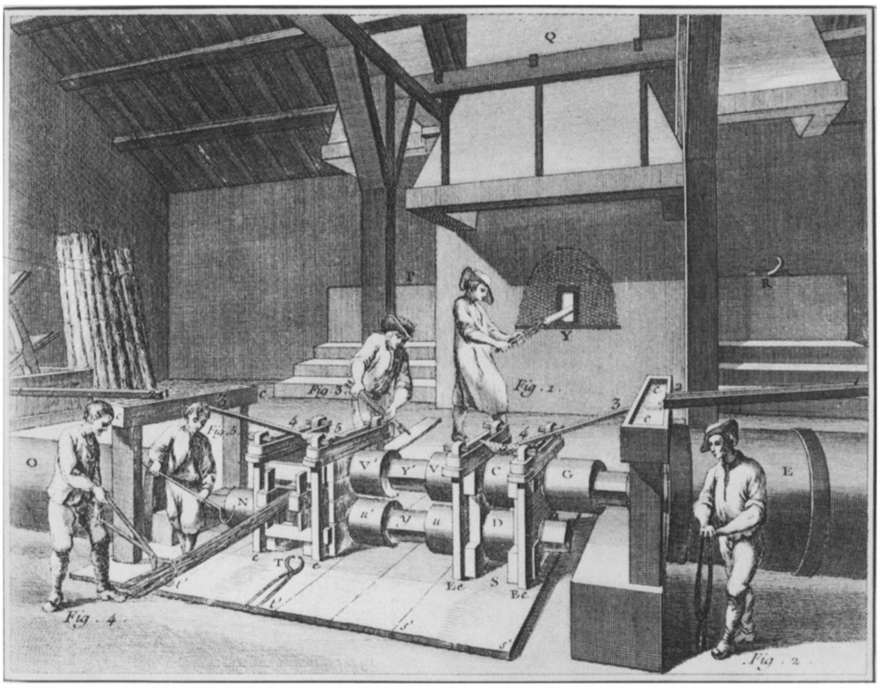
> decarbonized—at least as well as by the finery fire. This fact was admitted by all the forgemen who examined it. The blowing was usually continued from five to ten minutes, whereas the finery fire required over an hour. Here was the great saving of time and fuel, as well as the great encouragement to work the process out to perfection.[49]

Shortly after he received his patent, Kelly's company was bankrupt, a victim of the depression of 1857.

It was 1864 before the first Bessemer steel was produced in the United States. Around 1870 the principal early U.S. patents expired, but until that time organizations of manufacturers, such as the Pneumatic Steel Association, held and made available the U.S. patents of Kelly (for the process), Bessemer (for the machinery used), and those of other inventors who had made major contributions to the development of the Bessemer process, as it was known. Between 1880 and 1890 the production of Bessemer steel in the United States increased fourfold and its share of the growing market for iron and steel doubled.[50] By 1890 it accounted for over half of the total iron and steel output.

In 1861 William Siemens, one of an international family of inventors, received a patent on the gas producer, which was the final step in his development of the open-hearth furnace (fig. 4.23). By making gas from solid fuel, the producer allowed the use of cheap forms of coal, and the gas flames could be extended over a shallow tank of metal. Escaping gases were drawn through tunnels containing masonry grilles that held the heat. Entering air was admitted through another tunnel of similar form. A damper permitted switching the intake and exhaust functions between the two tunnels, preheating the air that fed the gas flames and extracting heat from gases as they were expelled from the furnace. In this way the temperature of the gas flames could be raised to around 3000° F. The effect of melting iron at such high temperatures was much the same as that of puddling; carbon was burned out of the molten metal. The ability to use scrap iron in the open-hearth furnace was a significant economy. Open-hearth production of steel was not nearly so "interesting and exciting" as the Bessemer process, and the United States was slow to replace the methods and

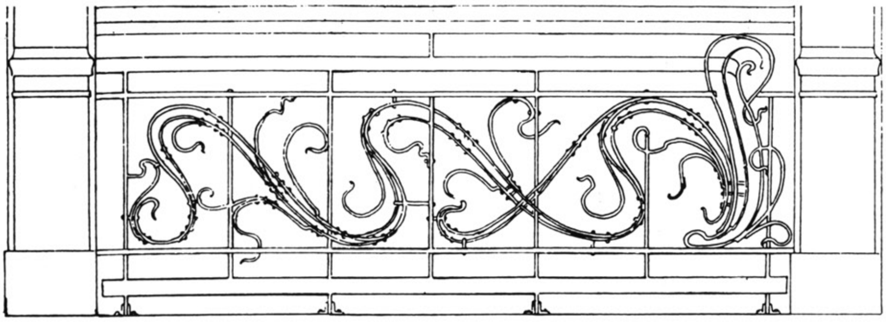




equipment it had adopted only a few decades before. Because of tariffs and price controls within the industry, it is hard to determine the relative costs of producing Bessemer and open-hearth steel in the United States. A governmental investigation around 1905 indicated that the difference in the total production costs for the two methods was probably less than 3 percent.[51]

* * *

Casting was a poor method for making thin and intricately shaped pieces of metal. By the seventeenth century there were machines in which flat sheets of soft metals, such as lead or tin, were passed between rollers to produce sheets that were larger, thinner, and more uniform than could be made by hammering. In the same period an Italian invention drew lead rods between steel rollers to form the H-shaped rods needed for fabricating windows.[52] Slitting mills used ridged rollers to cut straps and rods from sheets after they had been flattened between smooth rollers (fig. 4.24). Henry Cort in 1783 introduced grooved rollers through which wrought iron could be passed to amalgamate the lumps as they came from the puddling process. Cort's rollers produced bars of wrought iron 15 times faster than had been possible by hammering. With steam engines used as power, slitting and rolling became mechanized early in the nineteenth century, but for forcing out slag and compacting the ball of puddled iron, steam-powered lift hammers were not used until the middle of the century.



Bars, rods, and straps were rolled for those applications in which slender members of wrought iron were to be used in combination with pieces of cast iron, and plates and angles were rolled for the construction of boilers. Larger structural shapes were beyond the limits of practical production; 200 pounds was the largest mass that could be rolled, producing an I-beam 12 inches high and 6 wide but only about 5 feet long.[53]

Much of the early rolling of wrought iron was done in an effort to produce rails for the period's frantic construction of railroads. In 1820, wrought-iron rails were rolled in the form of a bulbous-headed T, the vertical leg being held by cast iron brackets. The familiar American T-rail, with a rounded top supported by an inverted T-shape, was introduced in 1830. Robert Livingston Stevens, president and chief engineer of the Camden and Amboy Railroad in New Jersey, designed the shape while sailing to England, where he went to buy rails and a locomotive. Upon reaching his destination, Stevens tried unsuccessfully to have the shape manufactured by major English ironworks, and months were spent before a Welsh ironworks succeeded in producing the rails.[54] For several decades most T-rails were imported from Great Britain, although some were rolled in the United States. The Trenton (New Jersey) Iron Works, one of the many investments of Peter Cooper, worked for at least five years before it successfully produced a T-rail in 1854. This rail, made 7 inches high, was not a successful addition to the types rolled at the time, but its use in building construction introduced the I-beam to the United States. It was planned to use this structural shape in framing the floors for Cooper Union, Peter Cooper's institution for training workingmen, but that work was delayed by the rush to replace the burned printing plant of Harper Brothers. A second delay came when the U.S. government ordered beams for an extension to the Assay Office in New York.[55] After these postponements, the wrought-iron beams were rolled for the completion of Cooper Union.[56]

Structural angles, channels, and I's were first shaped on two-high rolling mills, which had two grooved rollers,

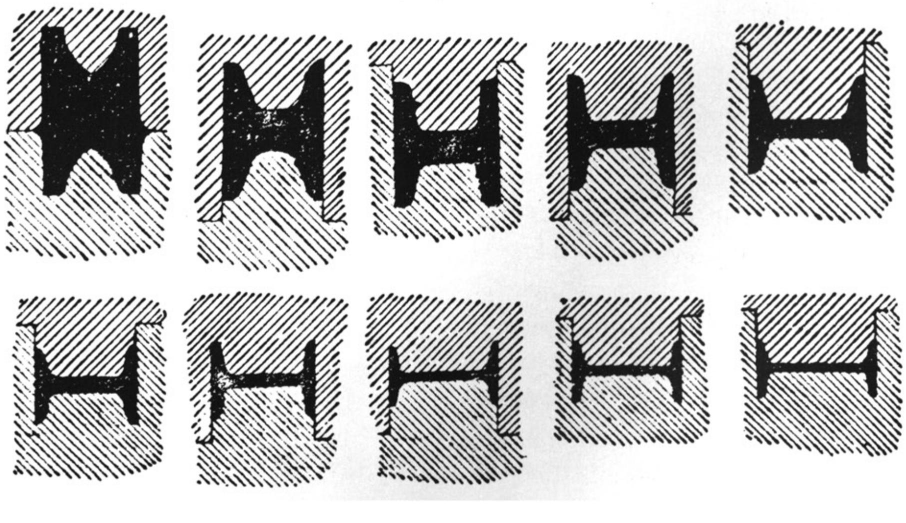
4.24 In this early water-powered rolling and slitting mill, flat strips of metal were made progressively thinner by the rollers at the right. After they were heated in the furnace at the rear, they were cut into rods (left). Power for this work was supplied by a water wheel turning the shaft at the right of the drawing (*E*). (Diderot, *Encyclopédie*, 1762–1777, "Forges," plate 3.)

4.25 The sensuous curves of Art Nouveau designs were particularly suited to execution in wrought iron. In this railing, designed by Victor Horta, the ease of bending wrought-iron straps is exploited, and rivets are emphasized as a punctuation of the pattern. (*Art et Décoration*, January 1897.)

one above the other. A first set of grooves at one end of the rollers roughly shaped the iron as it passed through, and each of the succeeding sets of grooves along the rollers refined the shape until it reached the desired dimensions (fig. 4.26). Successive passes through the mill required that the length of iron be lifted and returned to its starting place after each pass. The metal cooled during this time-consuming process, even more quickly when small sections were being rolled, and as a result flaws could appear in the flanges. The British long preferred "reversing" mills, in which time and labor were saved by changing the direction of the rollers' rotation each time the iron passed through the mill. In 1859 a British patent was granted for a three-high rolling mill for plates and sheets in which three rollers were mounted vertically. The middle roller was geared to rotate in a direction opposite to those at the top and bottom. By raising and lowering the plates, they could be quickly passed back and forth through the mill without the wrenching mechanical strain of reversing the gears of the machine or the costly process of reheating the metal.

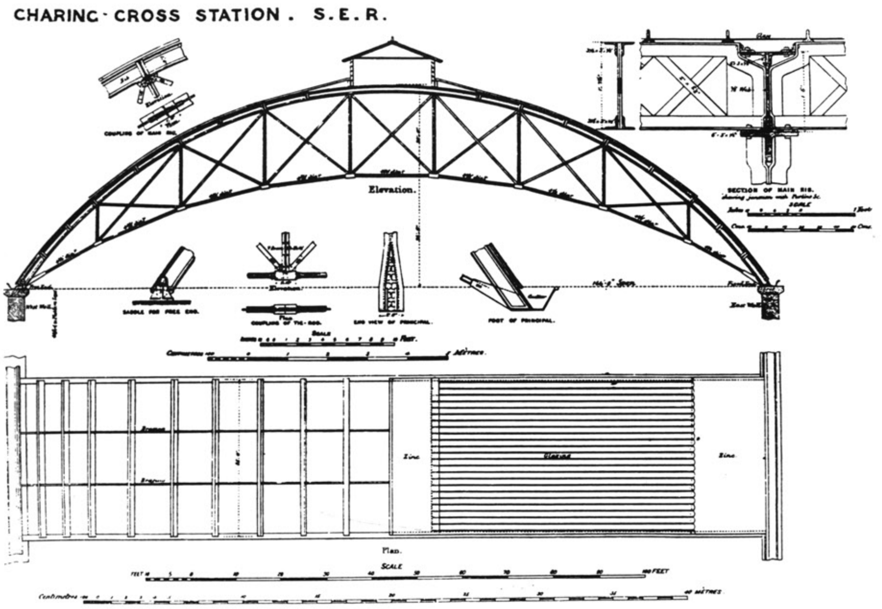
During the 1850s, British ironworks manufactured over three-fourths of the rails used by U.S. railroads. The rails shipped to the United States were usually the lower quality of British production, and British-made rails sold at a price well below those made in the United States. A worker in Pennsylvania rolling mills said that "had it not been for the use of putty, oxide of iron and the absence of inspectors there would have been but few rails shipped."[57] This ironworker, John Fritz, was destined to establish U.S. leadership in the development of rolling mills. The Cambria Iron Works, where Fritz was employed, produced only rails, and through the years the area's higher grade ores had been exhausted, leaving an ore that proved to be "red-short," brittle when red-hot. The losses due to flanges cracked in rolling were great, and in 1857 Fritz was instructed to build a new two-high mill. His dogged insistence that a three-high mill should be built at last persuaded the officers of the company. When completed, the mill was successfully tested on a Saturday morning, but that afternoon the building burned. The mill was rebuilt and proved so successful that U.S. companies built others within a short period. As Fritz commented at the end of the century:

> With the introduction of the three-high mill in 1857, the commencement of the great improvement in rolling mills and



4.26 To shape beams or girders, a series of rolls was required. The rolling mill was equipped with rollers having several grooves, each shaped to execute a single step of the process. Since the metal started at white heat and was finished at a "low" red heat, it was necessary that rolling be done quickly. The upper row of roller grooves, as shown here, was used to "rough" the shape of a beam, and the lower row finished the member. (*Encyclopedia Britannica*, 1911, "Rolling Mills.")

4.27 The truss that collapsed in 1905 at Charing Cross Station, London, failed near the bottom of the third vertical from the left. Investigation showed that the cause was a hidden flaw within the tie rod, a flaw that reduced the rod's effective area to about one-third of its total cross section. (A. T. Walmisley, *Iron Roofs*, 1888.)



> machines connected with them took place. The rolls were made larger in diameter, better fitted up, and a more powerful and a much better class of engines was introduced, larger and better heating furnaces were built, and many labor-saving devices were introduced. But with the marvelously increased production of Bessemer steel it was evident that a larger ingot must be used in order to prevent congestion in the pit furnaces and rolls. This, of course, involved the building of larger, heavier and more rapid working machinery.[58]

The rolling of structural sections from Bessemer steel became mechanized through the introduction of electric motors and the use of many labor-saving inventions of John Fritz and his brother George. By 1900 there would be around ten workers on the floor of a rolling mill that handled 3,000 tons of steel per day, an amount equal to a year's production before introduction of the three-high mill.[59]

As methods of rolling wrought iron and steel shapes improved, manufacturers began publishing sales literature to describe the shapes they produced and indicate their prices. These publications were not always helpful. One writer characterized continental sales catalogs as "misleading" and having "little information on much space."[60] German organizations of architects and engineers, who had become impatient with the inconsistency of the data they received, insisted on standardization, and in 1879 the manufacturers who served them set standard dimensions and soon afterward published their *Normal Profile Book*, showing the rolled shapes available for structures and shipbuilding. The shapes designed for this purpose were widely adopted in other countries that used the metric system.

In the 1880s the Carnegie Steel Company published its own standard shapes and discouraged orders for other shapes by establishing minimum quantities and imposing high charges for such orders.[61] The other steel makers that had joined the Carnegie pricing combine soon adopted those standard shapes. The formal adoption of standard sections by the Association of American Iron and Steel Manufacturers took place in 1895. Nine years later the British Engineering Standards Association established similar standards. Standardization would have been impossible without the full development of rolling practices and the increased ability to control the qualities of the steel and iron produced.

* * *

In the early 1850s, at the time when architectural use of iron became significant, at least half of the world's output of pig iron was produced in Great Britain. France had not yet undergone extensive industrial growth and its railway system lagged in development. Only at the middle of the nineteenth century did French industrialization begin to demand appreciable quantities of iron, and it was then that large-scale producers of metals began to replace a scattering of small French ironworks. German industrialization was more rapid, and there the governmental role was far greater than in other major European countries or the United States. With the exploitation of rich coal deposits in the Ruhr basin, beginning in 1840, Germany moved toward increased production of iron, assisted by much scientific knowledge of metallurgy and the frequent importation of English experts. The peak of English iron production came in 1880 and thereafter it remained relatively constant for many years. During the period from 1880 to 1908, worldwide production doubled, largely due to the fact that Germany's output increased four times and that of the United States more than five times.[62]

From 1865, when the Bessemer process and improved rolling mills were established in the United States, to 1907 production of pig iron in the United States steadily grew, reaching about 26 million tons, more than 30 times the production at the start of that period.[63] A major problem in U.S. production of iron was the distance between the mills and new supplies of Lake Superior ore; the mills were located where there was an ample supply of coal but the deposits of ore had been exhausted. By 1907 there were reports that the quality of Lake Superior ore had deteriorated, but the supply was immense, and only 12 percent more ore was needed to produce a ton of pig iron than had been needed ten years before.

Despite the enthusiasm with which metal construction was accepted, not all experiments in iron and steel construction were successful. The mathematics of theorists had not been reduced to accepted formulas for the use of iron, and there was considerable disagreement about the action of structural shapes and the characteristics of the metal used. It has been said about the 1840s in England:

> It must also be remembered that bridge engineering made rapid progress, because after the inauguration of the railways, this industry was of sufficient importance to attract the best engineering brains in the country. Professional engineers, however, found nothing interesting in the simple columns and beams supporting the floors of buildings of solid construction and limited height; while the architect, with his multifarious duties, could not find the time, even were he so disposed, to master the intricacies of the new materials.[64]

The majority of engineers at that time came from a background of practical work as millwrights, instrument makers, or other crafts, and although England led in the production and utilization of iron, France and Germany were much farther advanced in the education of engineers.

A cotton mill at Oldham, Lancashire, collapsed in 1844, killing 20 workers. The structure failed at one end where, instead of the iron beam being evenly loaded by brick arches,

4.28 When there was concern about the Crystal Palace's rigidity under the footsteps of visitors to the Great Exhibition, soldiers were summoned to test the girders that were to be used. A few testing laboratories could verify the strength of materials and test the key parts of an assembly, and often bars of iron or bags of sand were stacked on portions of a completed structure to determine its strength. For an additional system used to test girders of the Crystal Palace, see figure 15.7. (*Illustrated London News*, 1 March 1851.)

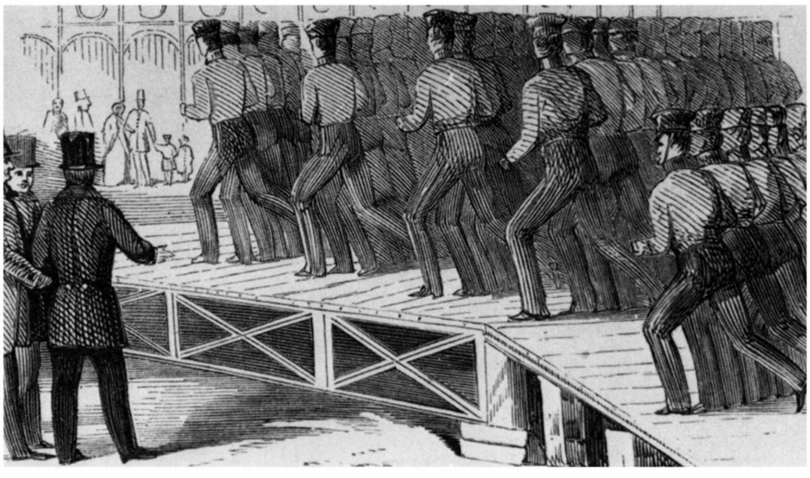
transverse secondary beams rested on it in the center of the span. This produced a stress greater than that in typical spans of the building. The report prepared by a governmental investigation makes it apparent that the builder of the mill had been unaware that the beams in question had been stressed more than twice as severely as others in the mill.[65] Other mill buildings failed, usually because of similar misunderstanding of the loads that bore on the members, as well as naive interpretations of the physical characteristics of iron beams and columns.

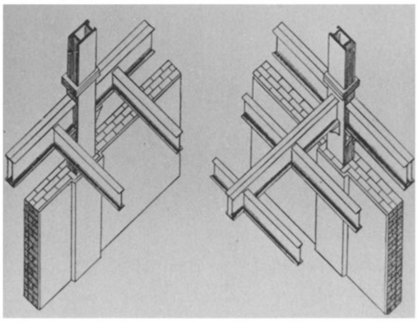
Another kind of problem was exemplified by the failure of the train shed at Charing Cross railway station, London, in 1906. Crescent-shaped trusses, built in the early 1860s, spanned 164 feet and were made of wrought iron, tension being taken by tie rods between 4 and 5 inches in diameter (fig. 4.27). One of the tie rods failed because of "concealed flaws, which may grow in size under continued tensional stress, although in itself that stress may not be exceptional." The fault had not been detected when the tie rod was tested before assembly of the truss. The investigator's report recommended the structural safeguard of redundancy by "duplication or strengthening of the main tension members."[66] Certainly, if there were any question of the material's soundness, two or more members used together reduced the risks that might result from an undiscovered flaw.

Direct testing of structure was the usual manner of verifying the stability of a design and the quality of materials. Before the Great Exhibition opened in 1851, soldiers were marched about the galleries of the Crystal Palace and cannon balls were rolled along them to prove for the public the reliability of the structure (fig. 4.28). Two years later, when wrought-iron lattice girders arrived in Ireland for erection of the Dublin Exhibition building, officials noted that all the girders' diagonals were made of flat bars. Test girders were loaded with heaps of stone, and the bars bent under the compressive forces present. Systems of testing promised an increasing ability to avert failures.

Conservatism was a frequent, though often misguided, guard against failures. In 1859, when the Bessemer process for making steel was in its early stages of development, the Board of Trade prohibited the use of steel in English bridges, a restriction that remained in force until 1877. Unlike the early use of reinforced concrete, the introduction of steel building construction did not have the advantage of competitive enthusiasm on the part of manufacturers or engineers, being overshadowed by activities in construction of railroads and bridges.

The sole distributors of rolled joists to the building trades were merchants who neither possessed nor professed any technical knowledge. Compound girders and the majority of joists with workmanship were imported from the Continent, or at times such work as holing or cleating was performed locally by blacksmiths.[67]





4.29 There were basically two ways of laying out skeleton construction. In the drawing at left, girders run along the perimeter of the building, supporting both the wall construction and floor beams. In the drawing at right, girders on the perimeter carry only the wall, and other girders perpendicular to them support the floors. (*History of Real Estate, Buildings and Architecture*, 1898.)

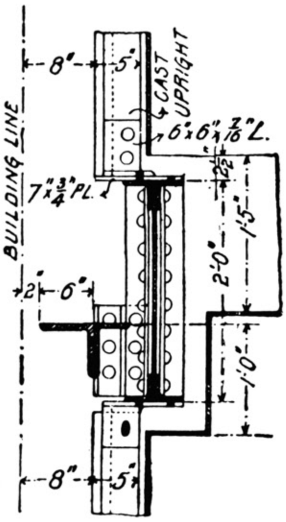
4.30 The Reliance Building (Chicago, Burnham and Root, 1895) employed terra-cotta facing over masonry walls. The framework (left) and its finished state (right) are shown for a spandrel wall beneath a window. (J. K. Freitag, *Architectural Engineering*, 1895.)

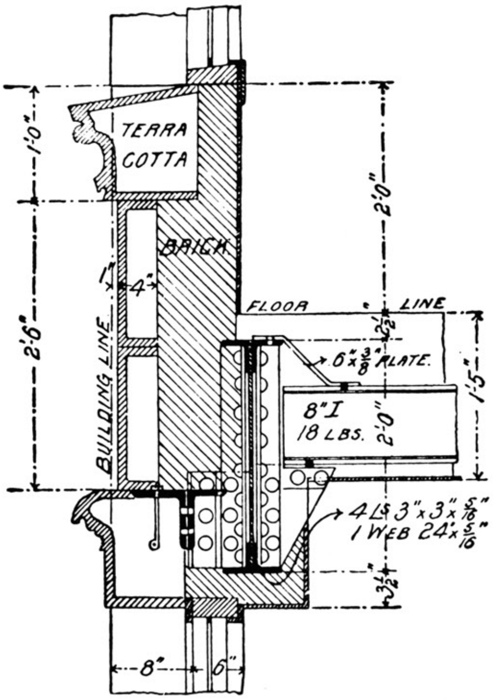
Steelmakers in the United States were more aggressive as salesmen. In 1895 an English speaker pointed out that "when anyone required an hotel or building even fourteen storeys high, he was informed by Mr. Carnegie's engineers not only how to do it, but that they were ready to undertake to do it for him."[68]

* * *

Early in the nineteenth century, wrought iron and steel could not assume forms as intricate as those that had been cast. Even elementary shapes, such as angles and T's, were beyond the capabilities of the earliest rolling mills, which could produce little more than straps and rods. In the 1830s there were attempts to fashion inverted T's by using U-shaped bolts or straps to fasten a vertical plate to a horizontal plate, but such expediencies did not utilize the full strength of the metal.[69] It was more effective to shape a T by riveting together two angles, formed by hammering plates of wrought iron. Such combinations depended largely on the use of hot rivets. Cold rivets had long been known, but hot rivets, introduced in the shipbuilding industry, provided stronger connections for the construction of bridges and buildings. As they cooled, the rivets shrank, firmly holding metal plates together and insuring frictional forces that prevented movement in the connection, a much firmer connection than had been provided by bolting cast iron. Cherry-red rivets were not so hot that they would alter the quality of the wrought iron around them, and girders and columns could be assembled from small and simple shapes. A riveted girder, about 19 inches high and 7 inches wide, was displayed at the French Exposition of 1849. Over 20 years later the situation was described by an engineering official of the government: "Since at that time there was not yet in France any application of this sort of construction and since no one could foresee the extent of advantages arising from it, nobody paid attention to this example and it was not mentioned in the report of the [exhibition] jury."[70]

England, more advanced in iron production and more actively expanding its railway system, was quick to adopt riveting. Construction of railway bridges and buildings had long been dominated by the use of trusses, arches, and girders that were made by bolting cast-iron members with tension rods and straps of wrought iron, but this combination was much less popular after the failure of the Dee Bridge in 1847. The following year the structural use of riveting was introduced in construction of the tubular wrought-iron bridge over the Menai Straits. Box girders, with plates and angles riveted together in a hollow rectangle, afforded great resistance to lateral bending in the bridge. There were shapes devised that provided tubular forms at the top of inverted T's, but they were seldom used. Instead, the I-shaped girder made of four angles and a single vertical plate was the one most often used in building, because it was easily assembled and could be painted to prevent rust.





At first, riveters worked in pairs, each wielding a hammer. By alternating their blows, they could quickly spread the point of the red-hot rivet. Steam-driven or hydraulic riveting hammers were stationary and had little use in building construction. A compressed air hammer, introduced in 1865, was applicable, but it did not become common until the following century when tools operated by compressed air were more generally used.[71]

Among the heroes of skyscraper construction were the riveter and his crew. As the uppermost beam of a skyscraper was swung into place, passersby on the street could spy the riveting crew setting it in place as their forge was moved to a roost made of a few planks across beams below. A 1930 newspaper story described the work of the riveting crew:

> Four men make up a riveting gang: the heater, the catcher, the driver and bucker-up. A youth in training for a riveter's career—he is called the rivet-jack—does the miscellaneous errands. He goes for new supplies and fills the water bucket. He stands beside the heater, who presides over the forge, a soft-coke burning chalice with a rotating blower that rouses the fire to efficient malevolence.
>
> The heater puts eight or ten large rivet spikes into his forge at once, burying them in the flaming coke. When the rivets are red hot and the rest of the gang is ready for them he takes a pair of slender three-foot tongs and picks out a likely looking specimen. With an easy underhand throw he tosses it through the air, for all the world as though he were merely discarding it. The flame-colored lump of steel sails straight for the catcher's head. He observes its flight with attentive nonchalance, his arms at his sides. When the red

4.31 Steel framework and terra-cotta surfacing meant that buildings could be erected quickly. The photograph at left shows Louis Sullivan's store for Schlesinger and Mayer (Chicago) as it appeared on 23 March 1903; center photograph on 31 March; and right photograph on 11 April. (*Brickbuilder*, May 1903.)

> hot missile is almost within six feet of his eyes . . . he lifts his right hand with an easy unhurried motion and catches the rivet in a battered tin can. Then he fishes it out with a pair of tongs he holds in his right hand, taps it on the beam he is standing on to remove any cinders and sticks the rivet into the steel plate. . . .
>
> A moment later the roar of a riveting hammer goes up. The bucker-up holds the rivet in place with the dolly bar, a heavy cylinder of steel capable of withstanding the shattering drive on the other end. Then the driver takes the yard-long riveting hammer with its trailing air hose and smashes the end of the rivet into a cap. That takes only a few seconds. The metal cools quickly, and for a minute or two New York's most popularly denounced noise is stilled.[72]

The work combined those factors of danger and skill that excite popular admiration. In the 1920s a championship riveting gang was acclaimed for setting a record by driving 308 rivets in 37 minutes.

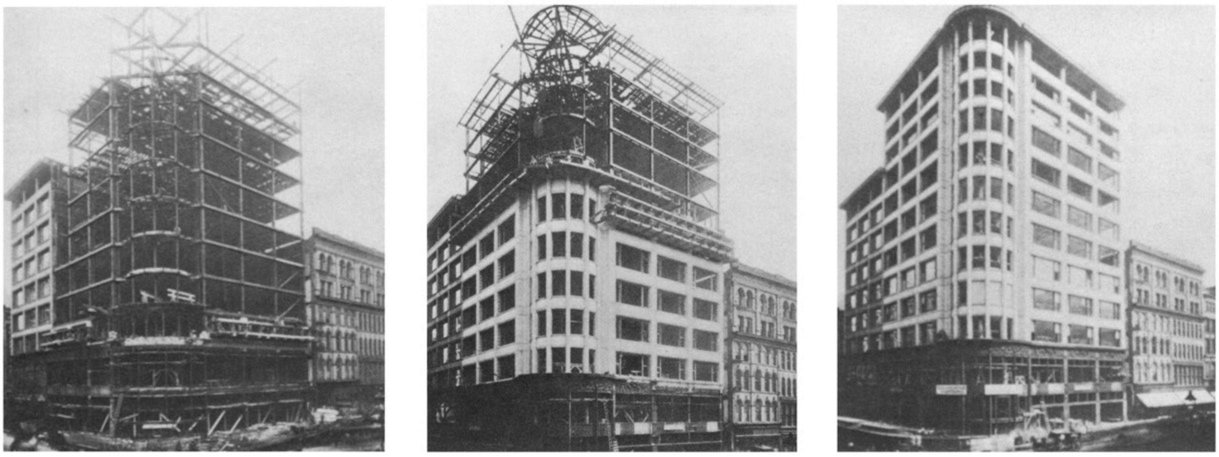
There were several structural advantages to the use of arc welding, which had developed from the electric arc lamp, and there were savings in the manpower required, but noise was the factor "behind most of the inquiries which are continually coming from business men's associations regarding the possibility of doing away with riveting."[73] In the narrow canyons of streets in a downtown area, the nerve-wracking clang of riveters could quickly become an issue. Welding with an electric arc had been introduced around 1885, and metal wires later replaced the use of carbon rods. It was the end of the century before acetylene was available and the welding of structural steel became practical. Some techniques of welding were mostly developed in the United States, where there was need for welded pipelines to bring natural gas to northern metropolises, and oxyacetylene welding techniques became highly developed in France. Welded boilers could withstand higher pressures than those assembled with rivets, and after 1920 welded ship construction was introduced and exploited by Germany, where "pocket battleships" could be constructed within the limits imposed by treaty at the end of World War I.[74] It was 1940 before electric arc welding of steel was well developed, spurred by wartime needs.

* * *

A first step toward skyscraper construction was the use of cast-iron interior columns rather than thick masonry walls and piers. Next, wooden girders were replaced by iron beams and wooden floor framing filled between. Then the search for fire-resisting construction led to spanning between iron beams with brick arches, hollow terra-cotta units, or reinforced concrete. A system of metal framework was developed that was fundamentally orthogonal yet could be adapted to the irregular forms that might be required by irregularly shaped building sites.

First this system took the form of "cage" construction, in which the iron and steel framework carried all floor and roof loads of a building while the surrounding masonry walls were self-supporting. This form of construction was strongly associated with New York and that city's architects, and that association may have resulted from the fact that New York building regulations stipulating wall thicknesses made little distinction between load-bearing walls and those that were nonbearing.[75] Some architects strongly favored cage construction, and in 1896

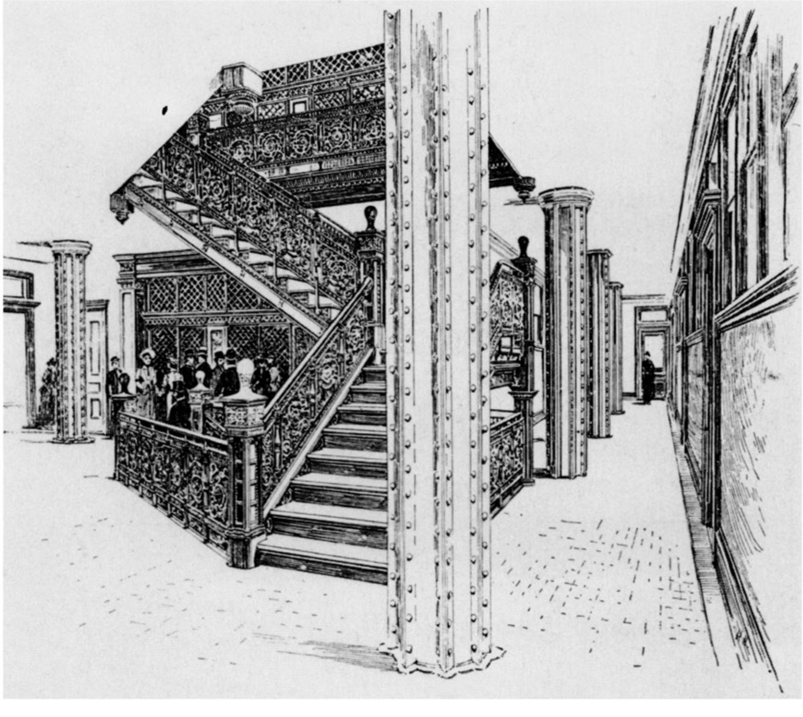
George B. Post insisted that if an exterior wall were sufficient to protect the metal frame of a building from water penetration and fire, the wall would be thick enough to support itself.[76] This, of course, could only be true within a very limited range of building heights.



The second system, surviving to the present, was called "skeleton" construction, and it supported masonry walls on the metal framework (fig. 4.29). Traditionally the thickness of masonry walls had varied with their height; a handbook from the middle of the nineteenth century recommended a thickness of at least one-twelfth of the wall's height.[77] With buildings of many stories this rule of thumb was not followed precisely, because linkage to other parts of the structure, intersecting walls, and the shape of the wall itself usually added stability. When the masonry of exterior walls was supported at each floor level, their thickness needed only to be sufficient to stiffen a height of around 12 feet against wind pressures and to protect the building's frame from water and fire.

Skeleton construction permitted flexibility in scheduling construction of a tall building (fig. 4.31). Once the steel framework was in place, work could proceed without the necessity of slowly moving upward until the structure's full height was reached. In the 1890s at least one Chicago building was enclosed in masonry from the top down, and in New York, when a contractor encountered delays in delivery of cut stone for the lower stories of his project, the masons completed the upper stories first.[78]

Columns of cast iron, the first sort to be used, were cheap and their many advocates recommended them as being more resistant to fire and rust than either wrought iron or steel. However, a single unseen flaw within a casting could cause failure of an entire column, and thicknesses were so unreliable that small holes were sometimes drilled to check them.[79] Manufacturers of cast-iron columns recommended increasing the factor of safety used, but that would have required heavier columns, making them fully as expensive as wrought iron or steel. Once buildings were so high that wind-bracing was an important consideration, it was generally accepted that the rigid riveted connections of wrought-iron columns were to be preferred to the bolted connections required for cast-iron columns. By 1890 cast-iron columns were no longer used in "important buildings."[80] Even before wind-bracing was strongly considered, cast-iron columns competed with other types. In 1862 the Phoenix column was introduced by the Phoenix Iron Company of Phoenixville, Pennsylvania. The Phoenix column was assembled by riveting together four, six, or eight pieces of wrought iron, each a segment of a circular circumference with outward flanges at the ends of the curved surface (fig. 4.32). In a later "improved" Phoenix column, vertical plates of metal were added in the joints and ran the full height of the columns. These plates were sometimes extended as brackets to which beams could be secured.[81] In 1862 the Z-bar column was patented in Germany, and it was introduced into the United States by 1888.[82] Four Z-bars were attached to a plate, two at each end of the plate, so that the resulting cross section resembled the letter H. An additional type, the lattice column, consisted of two channels (right-angle C-shapes) spaced as a rectangle with diagonal flat bars bridging the gap between them. In 1891 a Chicago engineer reported that the Z-bar column was the one most used there, but in 1924 another Chicago engineer stated that H-columns (rolled steel sections and a recent addition to the alternatives for columns) were prevalent.[83]



Calculation of the stresses in metal columns was complicated by the fact that they were often complex shapes built up from a variety of rolled shapes (fig. 4.33). Even if iron or steel members were part of the assembly, other pieces were added to make the section more nearly square and obtain a larger proportion of the metal far from its center. It was well into the twentieth century before rolling methods had advanced sufficiently to make it possible to produce wide-flange sections for columns, square H-shaped members with metal concentrated at the outer edges.

Before the advent of the passenger elevator in the later nineteenth century, commercial buildings were constructed to a maximum height of about six stories (the limit imposed by the effort required in stair-climbing), although rental area above the fourth floor was seldom profitable for the buildings' owners. Early elevators made it reasonable to extend construction to a height around 10 to 12 stores, but, according to Dankmar Adler, at that time the high price of iron discouraged construction above 100 feet tall.[84] There were other difficulties. At the height of 12 stories, exterior walls that were needed to carry floor loads occupied an excessive portion of a building's ground-level floor area, the level of the building that leased for the highest figure per square foot.

By the end of the nineteenth century, skyscraper construction methods had eliminated the necessity of massive ground-level piers of masonry, but it was widely assumed that economically sound construction of office buildings would never exceed a height between 16 and 20 stories, because beyond that height the rentable floor area consumed by elevators became excessive. Only after the development of the electric traction elevator and the introduction of zoning systems for elevator service did heights become virtually unlimited by technology.

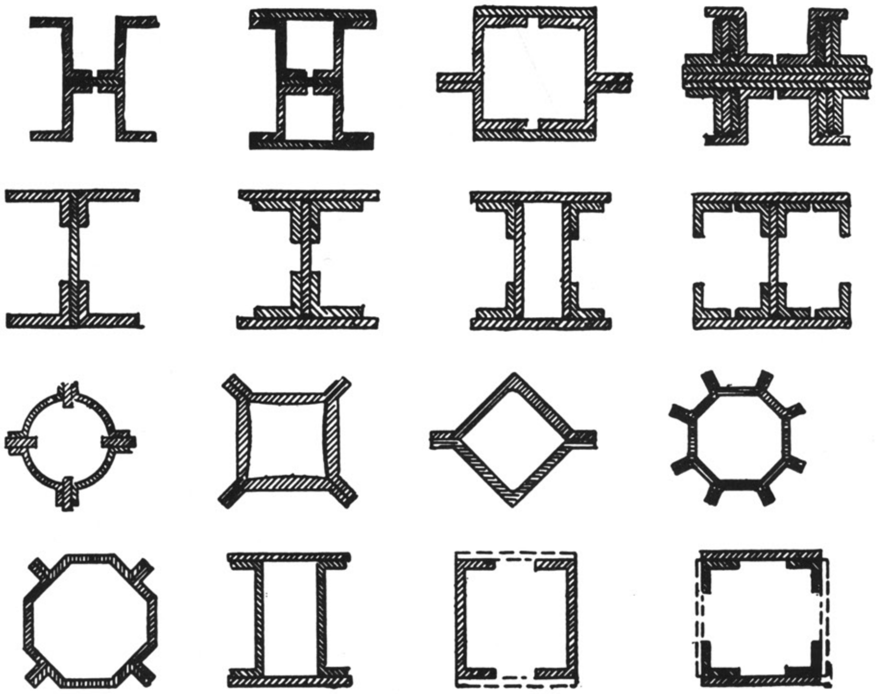
When the height of Chicago office buildings with elevator service had reached nine stories, the upper levels were still not popular with tenants, and buildings with their foundations engineered to support nine stories were often initially limited to seven (fig. 4.35). In time, however, tenants came to prefer the light, quiet, and airy offices available at the upper levels of tall buildings. In fact, noise was a factor of sufficient importance that some owners themselves paid for the application of asphalt to the cobblestone streets alongside their buildings in order to secure quiet for offices located in the lower stories.[85] Considerable prestige was attached to businesses' having offices in new skyscrapers, and there was extraordinary profit to be made from building even 12-story structures on land that had been bought at prices that reflected the income expected from six-story buildings. More and more skyscrapers were built.

As early as 1889 there was resistance in Chicago to the construction of taller buildings.

> It came first from the owners of property on the edge of the main business district and on secondary business streets who wanted business to expand laterally rather than vertically. Second, it came from the owners of some skyscrapers already erected who wanted to enjoy a monopoly advantage. Third, it came from owners of old buildings who objected to the assessment of their land for taxation on the basis of its use for a tall building.[86]

In 1893 these groups secured passage of an ordinance limiting the heights of buildings, but by then an oversupply

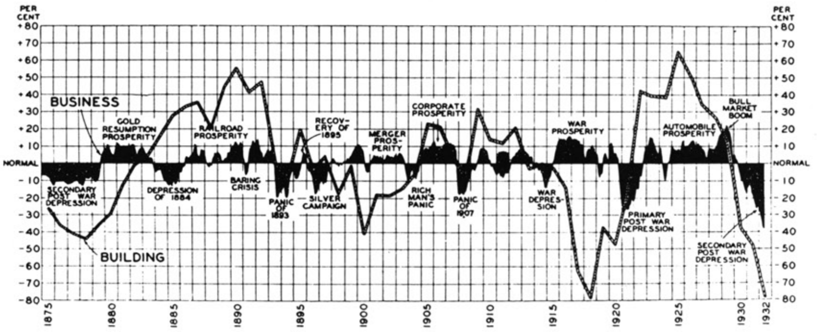
4.32 The World Building (New York, 1891) used an iron and steel interior frame in which richly decorated stair railings contrasted with the rows of rivets on patented columns. The 13 stories of outside wall were load-bearing and at street level the wall was 9 feet thick. (*Engineering Magazine*, May 1891.)



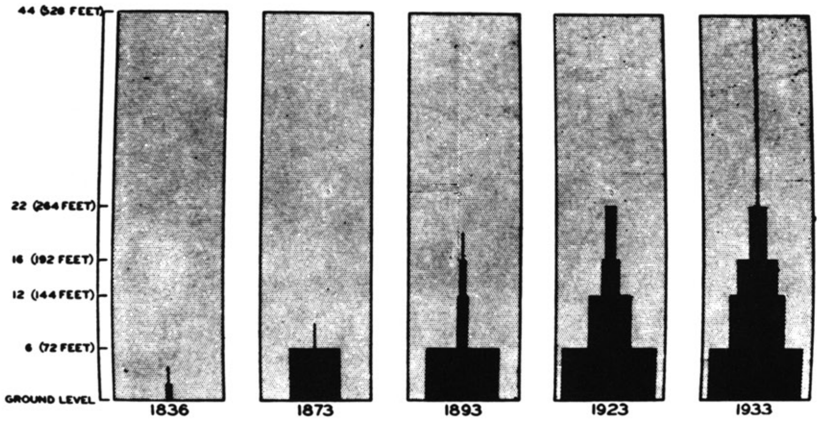
4.33 The two top rows of column sections are those made by riveting together plates, angles, and Z-bars. The bottom two rows show special and patented shapes, the last two being tied together by lattices, indicated by broken lines. (W. H. Birkmire, *Skeleton Construction in Buildings*, 1894.)

of office space and a nationwide financial panic had already brought a halt to the construction of skyscrapers in Chicago. In some other cities of the United States there was similar opposition to building tall.

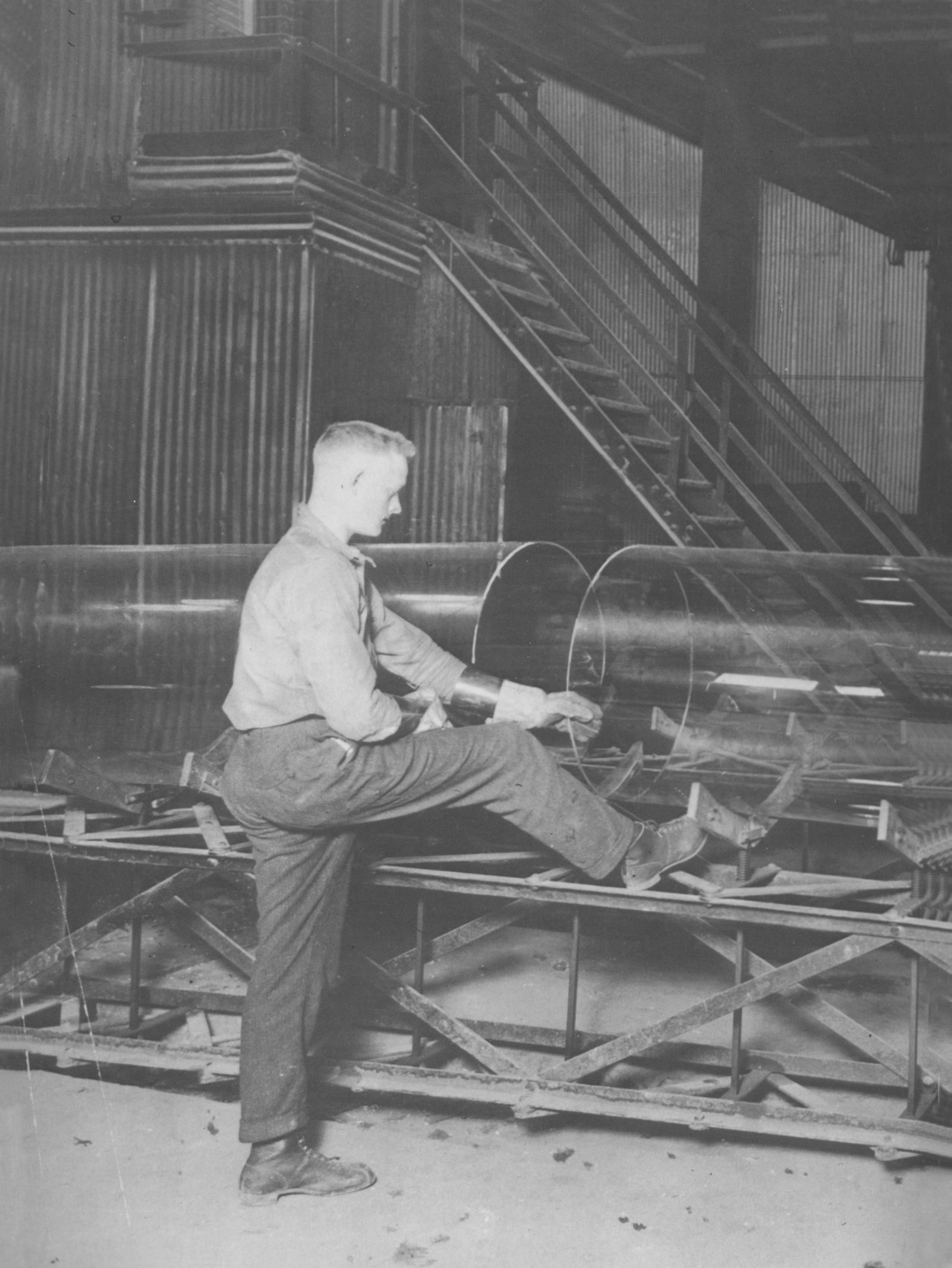
Until recently, the passion to build taller was on the whole limited to the United States. A British engineer could state that in 1904 "steel skeleton construction had barely got beyond the stage of rumours from America."[87] In the United States, however, activity responded to economic changes, a natural reaction since economics was the impetus driving the desire for tall buildings. Chicago in 1893 was the first major U.S. city to impose height limitations. Through the years those restrictions fluctuated from 130 to 260 feet, and in 1927 they allowed a height of 264 feet on the building line and greater height with setbacks. At the other extreme was Detroit, where it was spelled out that "Fireproof construction buildings shall not be limited in height."[88] Debate continued about the proper and economic heights of skyscrapers. Each decline in construction—World War I, the depression of the 1930s, and World War II—led to a demand for additional office space, and each boom saw buildings constructed higher than before. In 1902 the *Atlantic Monthly* forecast that "the mania for mere bigness is bound to give place to a better conception of corporate eminence," but that has not yet proved true.[89]



4.34 Building activity in the United States, when charted with general business conditions, indicates the periods of intense office building construction and the economic context in which they occurred. Conditions in an individual city may have varied significantly from the overall national conditions. (*Journal, American Statistical Association,* June 1933.)



4.35 A graph of the space occupied by buildings in the central business district of Chicago, 1836 to 1933. The black areas indicate the space filled by building masses at different heights of construction. (H. Hoyt, *One Hundred Years of Land Values in Chicago,* 1933. Copyright University of Chicago Press.)



Technics and Architecture

The Development of Materials and Systems for Building

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5

Glass

16th c.	Both crown glass and cylinder glass manufactured in France
1589	Fifteen glasshouses operating in England
17th c.	Increased use of cone furnaces in England
1615	Proclamation of James I forbids use of English timber in glassmaking
1665	Colbert attracts Venetian glassmakers to France
1690	English taxes to fund war levied on glass and windows
1848	Construction of glass-roofed Jardin d'Hiver, Paris
1850	Contract for glazing the Crystal Palace, London, awarded to Chance Brothers and Company
1856	Frederick Siemens's regenerative furnace, in which waste gases heat entering air
1860s	Introduction of continuous tank furnaces
1890s	Majority of U.S. manufacturers affiliate as the American Window Glass Company
1902	Machine for drawing glass cylinders patented (U.S.) by John H. Lubbers
1914	Production of drawn sheet glass commences in Belgium
1915	Production of drawn window glass begins in the United States using a development of the Colburn machine
1924	Production line for making plate glass at Ford Motor Company's River Rouge plant
1952	Pilkington Brothers Ltd. begins experiments leading to the float process

Wealthy Romans filled their windows with shutters, glass, parchment, or thin translucent slabs of alabaster. When used for this purpose, glass was cast by pouring the melted material into shallow molds or onto smoothed pieces of stone, and the sheets produced by this method ranged in thickness from ⅛ to ½ inch. Or perhaps, according to another opinion, most Roman window glass was made from blown cylinders, slit and flattened in a way that will be described later.[1] In the medieval period, linen or paper were more common materials for closing window openings. For the few who could afford glass, the window sash became a valued property. As late as the fifteenth century the casements of an English house usually belonged to the tenant rather than his landlord, and when a tenant moved he took his sash with him.[2] A sixteenth-century report on the condition of an English castle recommended that its windows be kept in place only during the presence of the lord of the castle and removed to storage upon his departure.[3] In Scotland, country houses of that period had no glass in their windows, and a royal palace had shutters in the lower half of its windows and glass only for the upper half.[4]

By the end of the eleventh century, Venice had assumed leadership in European glassmaking. Two hundred years later the craft had achieved a magnitude that attracted the attention of city officials. The Council of Ten commanded that all glass furnaces within the city be razed and rebuilt elsewhere, a ruling that caused glassmakers to relocate on the five small islands of Murano, just north of Venice. A severe fine was set for any glassworker who left Venice to work elsewhere, and in 1474 this punishment was changed to the penalty of death. The glassmaking industry of Murano prospered and became so large that more than 8,000 workers were employed, and the shops in which they worked filled a full mile along one street.[5]

In spite of the death penalty that had been imposed, Venetian glassworkers made their ways to other countries. Colbert, the finance minister who established the foundations of French industry, dispatched agents to Venice with instructions to smuggle out glassworkers who could bring Venetian glassmaking techniques to France. About a century earlier, Elizabeth I had granted a license for a Venetian craftsman to manufacture drinking vessels in a London workshop. Such licenses included the prohibition of competing imports, and English dealers in imported glassware loudly objected to the queen's action, warning of the immense quantities of wood that might well be consumed by the glassmaker's furnace. Thus began the migration to England of artisans from Italy, Holland, and France, many of the last group being Huguenots who fled religious persecution. Most countries enacted statutes that were meant to stem the flow of technical information and skilled craftsmen to other countries, but such measures invariably failed.

Always glassmakers were among the most prestigious of skilled workers. Those who made vases, goblets, plate glass, or mirrors were highly respected; the makers of bottles for wine and beer ranked low among glassmakers, although still higher than most other craftsmen. Venetian glassmakers had been raised to nobility for their craft, and some of those in France were made nobles either because of or in spite of their occupation. It is written that in Normandy the nobles who made window glass proudly disdained to blow bottles, a common use of poorer materials remaining from the production of window glass.[6] Bottles they left to the commoners employed in their glasshouses.

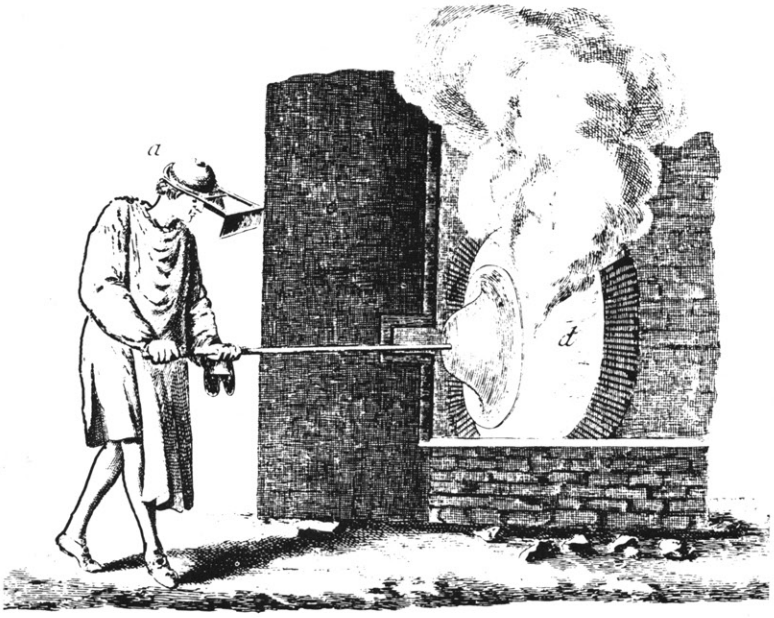
The social status of glassmakers may have resulted in part from the active market for their services. Window glass for buildings in England and northern Europe was purchased from other countries, but only if the building were sufficiently important to warrant the extreme cost. French glassworkers were brought to England as early as 675 to produce glass for a church, and "they not only did the work required but taught the English how to do it for themselves."[7] Despite this instruction, less than a century later German glassmakers were brought in to make windows for an English monastery.

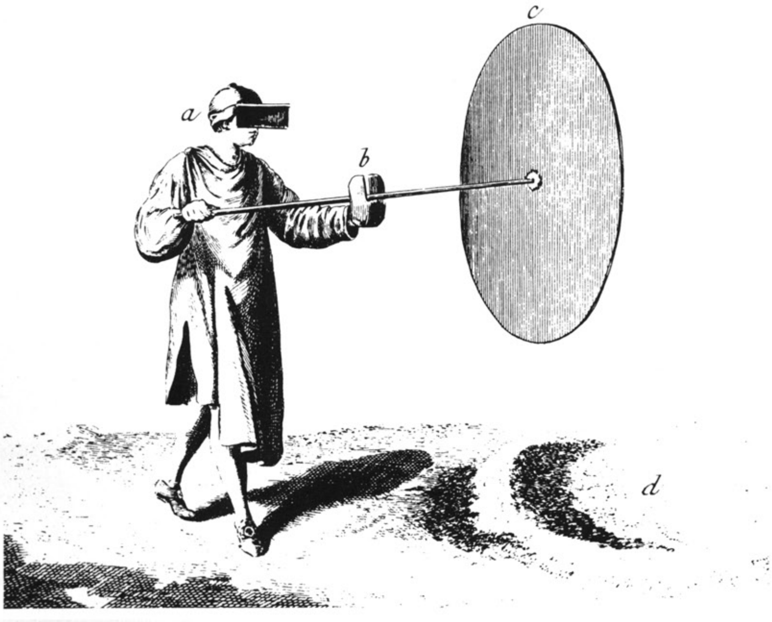
In France, two kinds of window glass were manufactured during the seventeenth century. The glassworkers of Lorraine, many of whom came to northeast France from Bohemia, blew cylinders, which were split and flattened. The Norman glassworkers of northwest France blew a glass sphere and altered it into a disk, a method that originated in the Near East in the fourth century.[8]

Normandy or crown glass, as it was called through its long period of popularity in England, was thin, and it glistened with a brilliant finish that had been glazed by the fire. Glass cools to a rigid state without crystallization, hence it can be gradually softened by heat without reaching a melting point at which it is suddenly altered from solid to liquid. This permits slight variations in its temperature to result in degrees of change in the plasticity of the material. To produce crown glass, the watery molten glass was cooled to a thick syrupy consistency. A mass of this viscous glass was gathered on the end of a heavy blowpipe. The gatherer dipped the pipe again and again, always taking glass from the center of a ring of fireclay, floating in the molten glass, from which floating impurities had been cleared. By rolling the mass against a slab of stone, iron, or wet wood, it was formed into a pear shape or a cone as it was blown. Repeated brief returns to the heat of the furnace softened the mass so that glassblowing could continue (fig. 5.1). Care was taken to shape a pointed projection on the bottom of the vessel being blown and to maintain it as the blower spun and enlarged his work. When blowing was completed, the shape of the glass resembled "an enormous decanter with a very flat bottom and a very short neck," having the pointed projection in the exact center of the bottom. An iron rod was attached to the bottom point with a small lump of melted glass, and the blowpipe was broken off by touching the glass around it with a cold piece of iron.

Then began the remarkable transformation of a glass vessel into window panes. The glass was spun in front of flames, until centrifugal forces widened the hole where the blowpipe had been removed. Slowly the vessel flattened into a circular disk with its rim doubled over, and then it "flashed" into a flat disk, making a sound that was compared to "that produced by quickly expanding a wet umbrella."[9] This circle of shining glass had remarkably little variation in thickness, except at its very edge and its center.

The completed disks of crown glass were placed on edge in an annealing oven with the center projection (bull's-eye, as it was known) spacing each disk so that the heated air of the oven could freely circulate around it. To





prevent brittleness, it was necessary to lower the temperature of glass slowly, a process requiring one or two days, depending on the amount of glass placed in the oven.

Disks of crown glass were sometimes as large as 6 feet in diameter. A disadvantage of crown glass was the unavoidable waste that resulted from cutting rectangular panes out of a circular shape. Before commencing his task, the cutter carefully inspected each disk for imperfections within the glass and scratches on its surfaces. The first cut was made a few inches to one side of the bull's-eye, and each cut thereafter had to extend through the piece remaining at the time (fig. 5.2). Even when cutters followed the charts provided by handbooks, waste would be about 10 percent, but all scraps were saved for use in filling future pots for the furnace. Waste might be higher when it was necessary for the cutter to make certain that only the smallest panes would contain the bubbles, flecks of dust from the glasshouse floor, or streaks caused by an uneven melting of the glass mixture. A perplexing problem was "hum," a white film that appeared as the disks of glass came from the annealing oven. As Henry Chance remembered in an address before the Society of Arts in 1856:

> The history of this "hum" is curious. It arose, probably in the first instance, from the deposition of sulphur from the fuel upon the surface of the glass. It became associated with the process of annealing, and buyers fancied that the more "hum" there was upon the glass, the better the glass was annealed. The manufacturers of crown glass, ever ready to accommodate themselves to the fancies of their customers, have taken the trouble to produce an additional "hum," by the introduction of sulphur in the kiln. The members, however, of the Glass Jury of the Paris Exhibi-

> tion, not being in on the secret of this hum, stoutly maintained that glass thus clouded must be bad glass.[10]

Although the film of hum could be brushed away, it was usually removed by immersing the glass in an extremely mild acid bath.

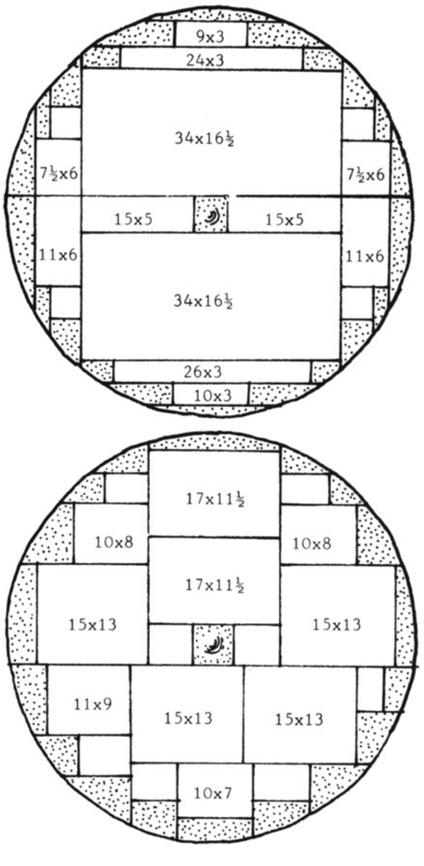
Crown glass declined in popularity on the European continent during the eighteenth century, being supplanted by cylinder glass, but in England its luster caused crown glass to dominate the market through much of the nineteenth century. Although crown glass could not attain dimensions as large as those of cylinder glass, its surfaces were clear and bright, unmarred by damaging contact with other surfaces. The English tax system in some ways favored crown glass over cylinder glass, but as late as 1856 it could be stated that it was the extreme "brilliancy of surface which has enable crown glass to maintain in England its position."[11] In 1880 crown glass was still produced in England, although it was no longer manufactured in the United States.

The other kind of glass, cylinder glass (or broad glass as it was also known), was made by blowing a round-ended cylinder and trimming off the ends to form a simple tube (figs. 5.3, 5.4). The tube was then slit once lengthwise and manipulated under heat until it lay flat. Because of its contact with the surface on which it was flattened, cylinder glass could not achieve the gloss of crown glass, but the rectangular shape from which panes of cylinder glass were cut permitted larger sheets to be cut than had been possible with crown glass. Cylinder glass was considered by many to be a reasonable compromise between crown glass and costly plate glass.

As with crown glass, the gatherer dipped the flared end of a blowpipe into the molten glass within a floating ring of fire clay. For making single-strength glass, which was 3⁄32 inch thick, the pipe would be dipped about three times until a mass of 15 to 20 pounds had been gathered. For double-strength glass, which was ⅛ inch thick, the pipe was dipped into the viscous glass about five times, resulting in a mass that weighed around 35 pounds. After each gathering of glass the mass was shaped, usually by rolling it in the concave hollow of a moistened wood block, until it had reached a pear-shaped form, the dimensions of which would determine the diameter of the cylinder to be blown.

When the gatherer had completed his task, the pipe and its accumulated glass were passed on to the blower, who stood on one of the platforms that extended outward from the furnace. Alongside these platforms ran trenches about 10 feet deep, and the mass of gathered glass was suspended into the trench. As the blower swung it back and forth the weight of the

5.1 By spinning, manipulating, and reheating the vessel that had been blown, glassworkers converted it to a flat circle of glistening crown glass. When the glass had hardened, it was detached from the rod and laid in a hollow shaped in sand. (Diderot, *Encyclopédie*, 1762–1777, "Verrerie," plates 13, 14.)



5.2 *The Crown Glass Cutter and Glazier's Manual* (1835) contained a host of diagrams showing ways to divide a disk of glass. All of the diagrams have approximately the same proportion of glass wasted, but the location of blemishes and a demand for certain sizes of panes could recommend the selection of one cutting pattern over others. (Drawn from W. Cooper, *Crown Glass Cutter and Glazier's Manual*, 1835.)

5.3 The making of broad (cylinder) glass is described in this eighteenth-century illustration. In the center is shown the slitting of the cylinder, preparatory to its entry into the flattening oven, from which it will be taken as a flat rectangular sheet. (Diderot, *Encyclopédie*, 1762–1777, "Glaces souflées," plate 36.)

5.4 At the factory of Chance Brothers, blowers made cylinder glass for installation in the Crystal Palace. At the far left, workers gather and prepare the mass of molten glass, which will be swung, reheated, and blown larger by the master craftsmen. (*Illustrated London News*, 21 December 1850.)

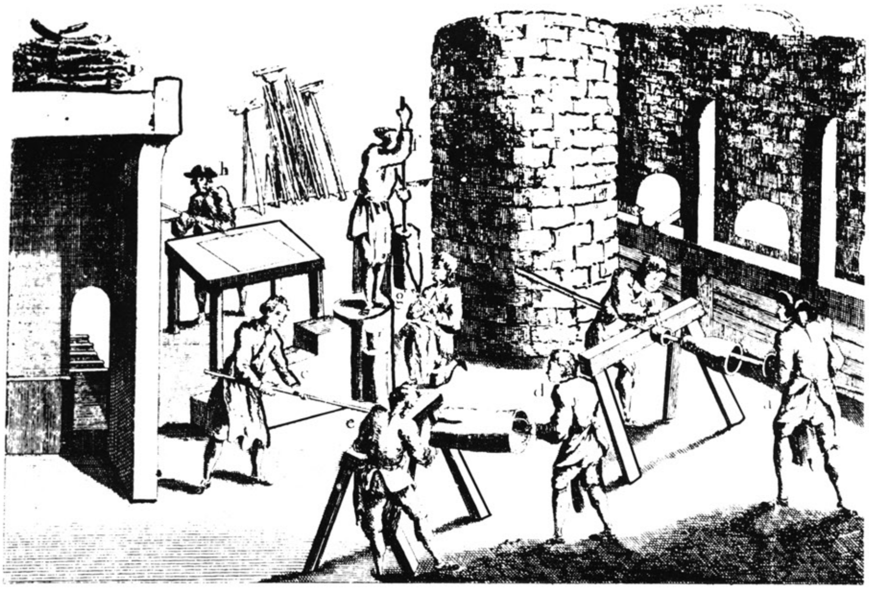
glass pulled the blown vessel into a long tubular shape. Periodically the work was returned to the fire for reheating. If the glass were overheated, threatening to lengthen so quickly that the walls of the cylinder would become too thin, the mass was swung overhead, cooling as the weight of the glass halted overextension of the cylinder. This continued—blowing and swinging, reheating, blowing and swinging again—until the walls of the cylinder reached the desired thickness. A blower's skill was judged largely on the accuracy with which he produced glass of a prescribed thickness.

The size of cylinders increased through the years. For 1844 an average size of 40 inches long and 9 or 10 inches in diameter was reported, but about 40 years later the typical cylinder was 60 inches long.[12] The largest cylinders were blown only of double-strength glass, and their weight could be handled by few workmen. It required extraordinary strength for the blower to swing the heavy cylinder like a pendulum, to hold it before the fire, and occasionally to whirl it upward into a vertical position. Once a cylinder of single-strength glass was completed, it was allowed to cool slightly. Then the mouthpiece of the blowpipe was sealed as the end of the cylinder was heated until expanding air within the cylinder blew out the softened end. For double-strength glass a lump of molten glass was placed on the end of the cylinder, its heat having the same effect.

It was the next phase of the work that most influenced the quality of cylinder glass. The finished cylinder was trimmed at both ends and slit down its length by a diamond or a red-hot iron running along the surface. With its slit upward, the cylinder was heated until it lay flat on the table. As the cylinder began to soften in the flattening oven, it was opened until it lay on the table "like a sheet of rumpled paper."[13] The flattener used a tool to rub the sheet of glass until it lay flat, and it was then moved into the annealing oven, where its temperature was slowly lowered. It was essential that the surface on which the glass was flattened should withstand high heat and maintain a finish as smooth as possible. The most common solution of this problem was the use of large tiles of fireclay, carefully leveled and polished. This "flattening stone" lay on a bed of sand and was 4 to 6 feet in each dimension, larger than the sheet of glass it would produce. The French often placed a sheet of glass over the stone, providing a smoother surface, although the glass had to be replaced periodically. To prevent adhesion of the two glass surfaces, the flattener would throw lime into the fire, producing a fine film.

Because of stresses within the flattened cylinder, its inside circumference being shorter than its outside circumference, sheets of cylinder glass were always very slightly bowed when they cooled. To avoid breakage in shipping, it was necessary to pack the sheets with those subtle curvatures parallel, and panes of cylinder glass were set in window sash with the curve bowing outward.[14] The flattening process was subject to myriad flaws that influenced the quality of the product. In 1856 the problems of quality control were described:

> Standing before the table of the "assorter," your eye lights upon a piece which, blown under an evil star, has imbibed in the glass-house every possible defect. The founder, skimmer, gatherer, and blower, have all stamped their brand upon it. It is seedy,—the vesicles, which were in the crown tables rounded by the rotary motion of the piece, [are] here elongated by the extension of the cylinder; it is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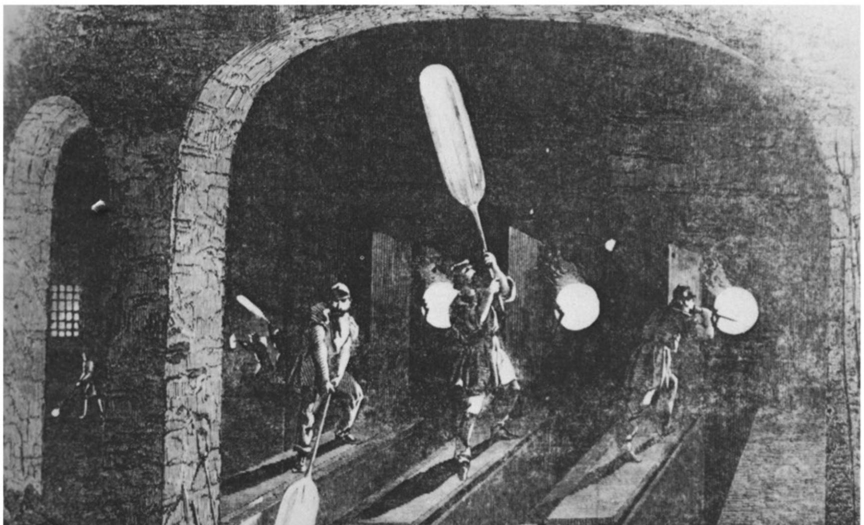


5.5 At the far left, a copper roller is ready to spread the glass that is being poured onto the casting table. After the glass hardens, bars are removed from the edges of the sheet, and the table is rolled to an annealing oven into which workers push the sheet of cast glass. (Diderot, *Encyclopédie*, "Glaces," plates 24, 25.)

> stony, disfigured with stony droppings from the furnace; stringy, thin threads of glass meandering over its surface; "ambitty," covered with stony speckles, symptoms of incipient devitrification; conspicuous with gatherers' blisters and blisters from the pipe—badly gathered; badly blown—thin here, thick there, and grooved with a row of scratches; and on this abortion the flattener chances to have exerted his most exquisite skill; it has passed through his hands unscathed, flat as a polished mirror, yet, from its previous defects, entirely worthless. Next comes before you a piece whose beginning was miraculous,—no seed, no blisters; it prospered under the hands of the gatherer and blower, and left the glass-house a perfect cylinder. But the crappie [tool] of the flattener marked it; the fire scalded it; dust fell on the lagre [flattening stone], and dirtied it; scraps from the edges of the preceding cylinder stayed upon the lagre, and stuck to it; the stone scratched it; and the heat of the annealing chamber bent it. Such are the difficulties to which every cylinder is subject—those of the glass-house, and those of the flattening-kiln.[15]

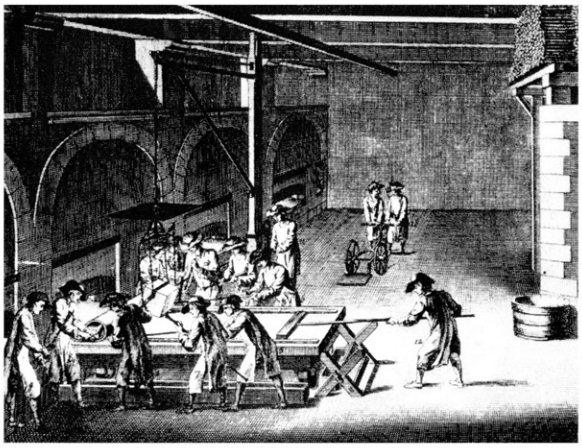
As methods were refined, the quality of cylinder glass improved. There was fortunately a considerable market for low-quality glass to be used in greenhouses, skylights, and other applications for which perfect clarity would have been a foolish luxury. English manufacturers had the opportunity of sending their worst glass to colonies, where tariffs penalized foreign competition. In fact, in grading English glass at one time the level just above "coarse" was listed as "Irish."

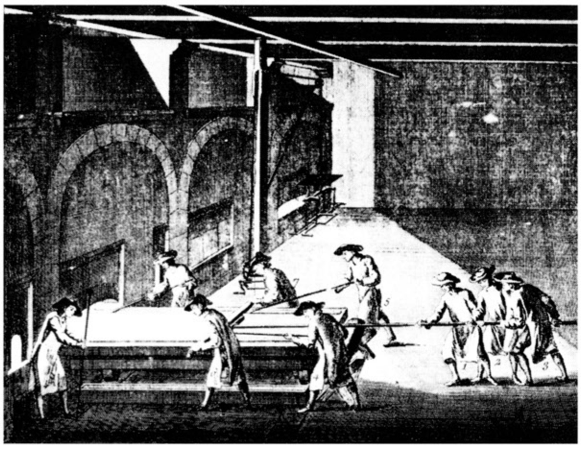
A market for the finest of glass rose toward the end of the seventeenth century. Courtiers, nobles, prosperous merchants, and ladies of society in France delighted in rooms with large polished mirrors and coaches with broad windows. Thick polished plates of glass were in high demand. Crown glass could not provide the desired dimensions from its half-circles, and for cylinder glass of the desired thickness, sizes were necessarily limited because the weight of a greater quantity of glass would have been unmanageable in the blowing process.

In 1676 the French government gave official support to Norman glassmakers' efforts to produce plate glass by casting. They had previously polished cylinder glass, but casting permitted them to manufacture sheets of glass that were both larger and thicker. As compared with blown glass, the casting process had the advantages of taking half the time, replacing blowers with workers at less than half the blowers' wages, and requiring fewer workers overall.[16]

For casting, a pot was heated in the furnace before molten glass was ladled into it. By levers or a system of pulleys the heavy pot was then moved to the casting table. The glass was poured between iron bars that marked out the size of the sheet and established its thickness. A heavy iron cylinder was quickly rolled over the viscous mass, achieving a uniformity of thickness seldom obtained in blown glass (fig. 5.5). Once sufficiently cooled, the sheet of glass was transferred to an annealing oven, where its temperature was lowered over the course of a week or more. Casting tables were first made with copper tops supported on masonry pedestals, a French construction that was soon adopted by the English. These surfaces sometimes cracked and in the 1840s it was possible to substitute large cast-iron plates, which were supported on rollers so that they could be wheeled from the furnace to the annealing ovens.

Once plates of cast glass had cooled in the annealing oven, they were laid on flat slabs of stone and fastened in place with a bed of plaster of paris.





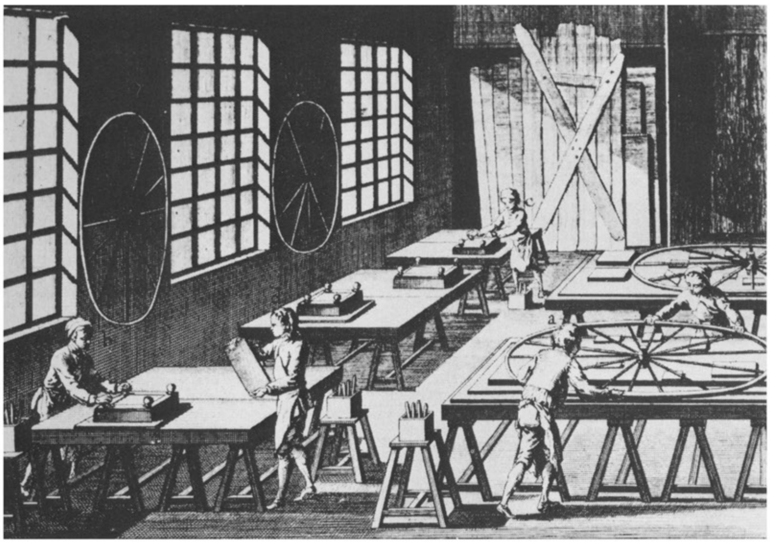
Over the sheet was mounted a wheel, with one or more smaller pieces of plate glass cemented to its surface (fig. 5.6). Between the two glass surfaces were fed water and sand, increasingly fine sand being used as the grinding progressed. After grinding was finished, the glass was polished with a paste of rouge, a ferric oxide (fig. 5.7). When those surfaces were smooth and fully polished, the sheets of glass were turned to grind the other sides. Grinding was a long, tedious, and costly task until steam power was first employed toward the end of the eighteenth century, and the expense of bringing the glass to a fine polish far outweighed the economies of the casting process.

A series of improvements to this method of making glass elaborated the simple process. At the start of the twentieth century, there was introduced a continuous annealing oven in which a series of preliminary ovens were followed by a tunnel about 300 feet long. The time required to cool the glass was thereby reduced from over 200 hours to little more than 3.

In addition, extensive mechanization of the grinding and polishing process reduced the time required to obtain a high gloss and greatly simplified the delicate task of turning sheets of glass so that their second surfaces could be finished.

* * *

In Daphne du Maurier's novel *The Glassblowers*, a father warns his daughter, "If you marry into glass . . . you will say good-bye to everything familiar, and enter into a closed world."[17] Glasshouses were usually isolated deep in the forests that provided their fuel, and the typical work force numbered between 25 and 50. Before the French Revolution the production of crown window glass in Normandy was restricted to four families having the rank of nobility.[18] Usually many of the workers in the glasshouse were related, and the reluctance of noble glassmakers to marry their daughters to plebeian artisans meant that there were frequently blood ties among the owners of nearby glasshouses. Whatever the reason for glassworkers having been granted nobility in some countries, their economic status was below that of other nobles, who were forbidden to engage in any occupation other than agriculture.[19] In some instances owners worked alongside the craftsmen in their glasshouses, but others limited their activity to supervision of the work.



Three workers customarily made up the team charged with preparing the disk or cylinder from which panes of glass would be cut. The required mass of viscous glass was taken from the furnace by the gatherer, youngest member of the team. The material was prepared by the assistant blower, and when readied it was passed to the master craftsman. Often this team was hired as a unit and the blower paid the other members of his group. The manager of a glasshouse provided the other workers that were required. A stoker tended the furnace and was commonly second in command at the glasshouse. Potmakers prepared the crucibles in which the glass was melted. For cylinder glass, flatteners were essential, and all types of glass were cooled by those who tended the annealing ovens. Basketweavers and packers prepared cut panes to be hauled away by carters, who also brought in the fuel gathered by a force of woodcutters. All of these workers were provided lodging and food by the owner of the glasshouse. Wives and children of the workers were hired, being paid one-half and one-third, respectively, of the wages paid men for the same work.

Between the owner or manager of a forest glasshouse and his workers there was a relationship somewhat similar to that of a feudal lord and the workers of his manor. The widows of workers and their children were pensioned or provided with jobs. When business was good, workers deeply resented the importation of foreign employees, but the manufacturers found it difficult to prevent their employees' leaving for jobs elsewhere.

When the London Company established its settlement at Jamestown, Virginia, the second ship sent there brought a group of Poles and Germans who had been selected to develop the manufacture of "pitch, tar, glass, mills, and soap-ashes."[20] The glasshouse they constructed soon fell into disuse, and in 1621 (only one year before the colony's first phase was ended by massacre) Italians were brought to Virginia to make bottles and provide beads for trade with the Indians. There were other attempts to make glass before the colonies revolted, but none lasted long, and the need for window glass was satisfied by imports or the substitution of oiled paper or cloth.

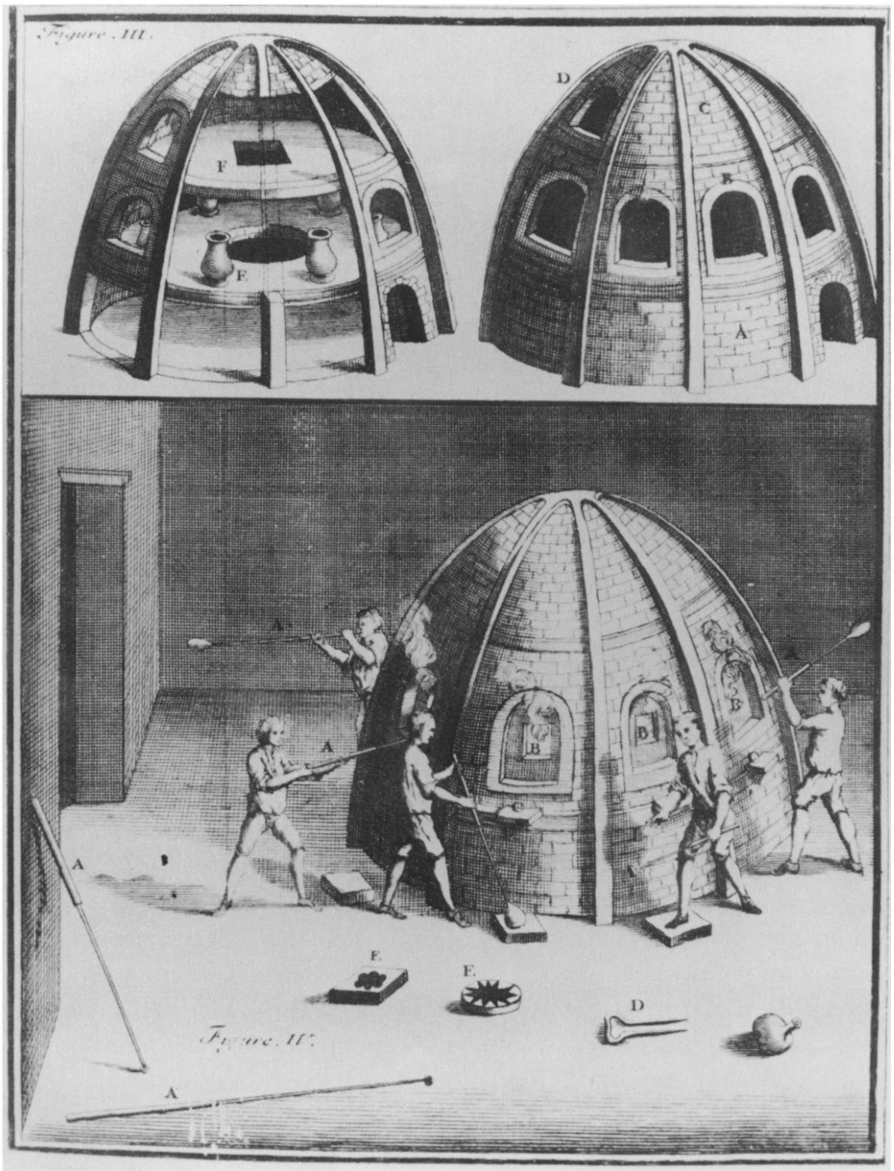
The first successful window glass plant in the United States was established in Boston shortly after the Revolutionary War with generous support of the Massachusetts legislature. About a decade later a German workman was employed, and the quality of the crown glass improved until "Boston window glass" was sometimes claimed to be superior to imported glass.[21] When a company was begun in Utica, New York, the owners dispatched agents to Boston with instructions to lure away indentured workers, but these recruits were arrested before crossing the state boundary. A new plant in Virginia attracted a large number of Boston artisans but soon closed, and several small glasshouses were begun by former employees of the Boston Crown Glass Company.

Pennsylvania was to become the center of early glass production in the United States; glassmaking there was begun by Albert Gallatin a few years before he was named Secretary of the Treasury by Thomas Jefferson. This glasshouse was isolated about 90 miles south of Pittsburgh, and it did not influence development of the industry in that area so strongly as a factory later established in Pittsburgh. Operating eight pots for the production of window glass, the second company may have been the first in the United States to employ coal as fuel, a great risk for a new factory in a young industry. Pittsburgh glassmaking flourished until its glasshouses employed 169 workers in 1815, but four years later, at the lowest point of the depression that followed the War of 1812, there were only a fourth as many workers.[22] Coal and sand were available in the vicinity of Pittsburgh, but some other materials had to be brought from far away. Saltpeter came from caves in Kentucky and also from Calcutta, and pot clay was brought from New Jersey and Holland.

The major investment in establishing a glasshouse was the careful construction of the furnace. The German metallurgist Agricola described glass furnaces in his treatise on mining, *De re metallica,* which was published in 1556. The furnace Agricola described had originated in southern Europe and was shaped like a large beehive. In the lowest of three ticrs, pots of raw materials were heated until the ingredients fused; the pots were then lifted to the middle level, where their contents melted and were available to the glassblowers; and the finished work was placed in the top level for annealing (fig. 5.8). Sometimes the functions of the top and bottom levels were fulfilled by separate furnaces. The beehive furnace and rectangular versions of it persisted for several centuries. Usually they were sheltered by barn-like structures from which the smoke

5.6 Cylinder glass could also be polished to eliminate traces of the flattening process. At left, small pieces of glass are fastened to stone slabs for polishing the large pieces on the tables. Several small pieces of glass could be fastened to the spokes of a wheel (right), which was spun to polish them as well as the sheet beneath. (Diderot, *Encyclopédie*, 1762–1777, "Glaces," plate 39.)

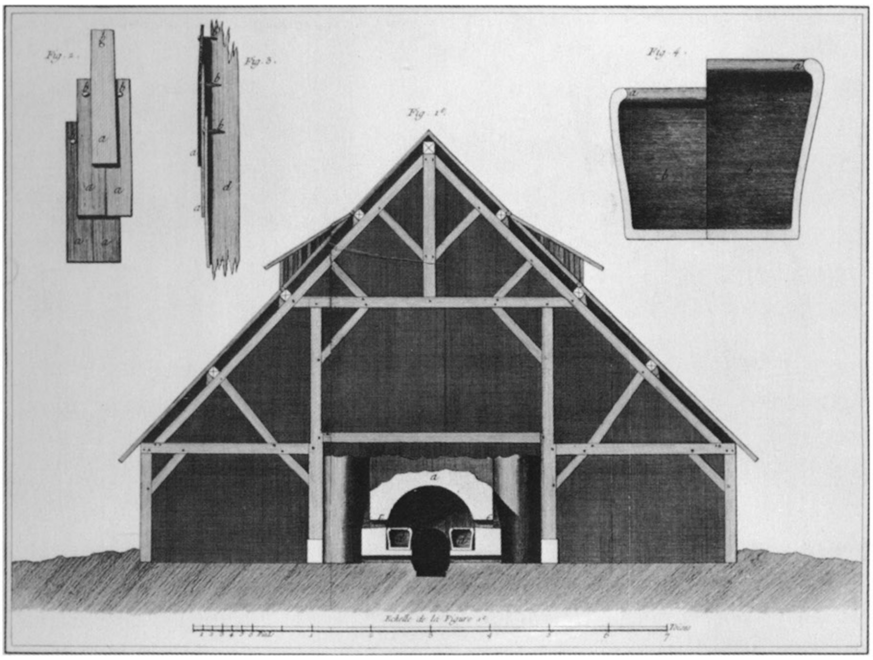
5.7 For the finest polishing of plate glass, always required for mirrors, rouge and felt pads were employed. Arcs of bent wood applied a constant strong pressure for the polishing. (Diderot, *Encyclopédie*, 1762–1777, "Glaces," plate 46.)



5.8 European furnaces of this sort were used from the sixteenth to the nineteenth century. The fire was built at the bottom level, glass was melted in the middle level, and the work was finished at the top. Beside each blower was a wet block of wood or stone against which the work was turned to achieve the desired shape. ("German" furnace, 1752. Courtesy of School of Materials, University of Sheffield.)

5.9 The masonry mass of a furnace usually occupied the central bay of the wooden structure that sheltered early glassmaking operations. Vents permitted smoke to be dissipated through the roof. (Diderot, *Encyclopédie*, 1762–1777, "Verrerie en bois," plate 4.)

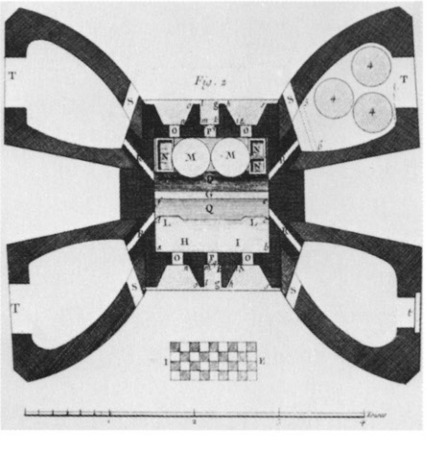
5.10 This French furnace for making plate glass had space for four pots (*M*). Heat passed into kilns at the corners, which were used to fire pots and the box ladles in which glass was taken to the casting table or to preheat materials that would be melted later. (Diderot, *Encyclopédie*, 1762–1777, "Glaces," plate 6.)

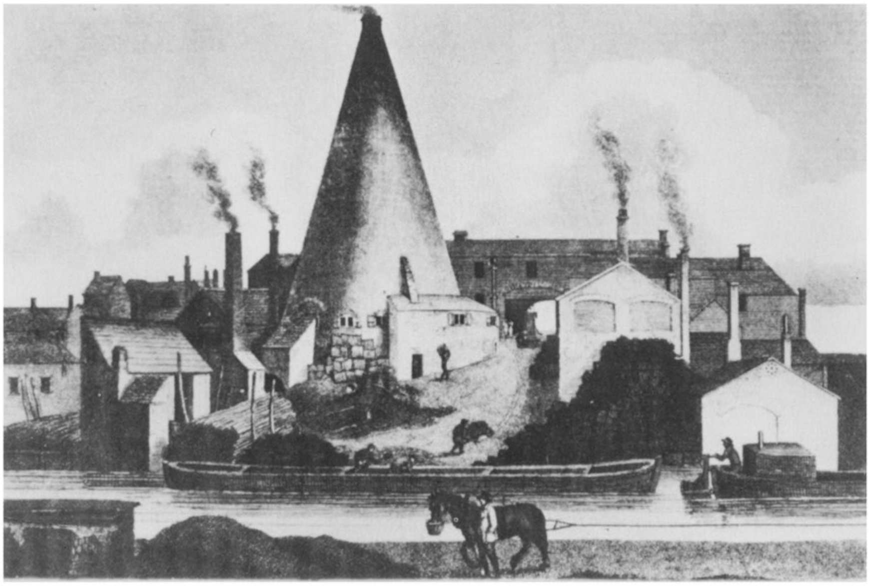


escaped through louvered openings in the roof (fig. 5.9).[23]

The use of coal as fuel led to development of the English cone furnace. There were several conditions that governed the design of efficient coal-burning furnaces. To generate sufficient heat for melting and refining the materials, coal required a stronger draft than wood. Profits rose as more pots and glassblowers could be fitted around a furnace. Waste heat could be utilized for related purposes, such as drying newly made pots, preliminary heating of charged pots, or annealing the finished glass (fig. 5.10).

The cone furnace was a tapered masonry structure, open at the top and measuring as much as 100 feet in height (figs. 5.11, 5.12). The entire cone acted as a chimney, creating a strong draft that pulled air through the furnace. Underground tunnels brought air to the coal grate, permitting large quantities of air to reach all parts of the fire, while the floor around the furnace remained unobstructed. Because soot from the conical top surface often fouled the pots of molten glass, a shallow inner dome was added with flues built around its edges. These peripheral flues drew flames from the central fire to the





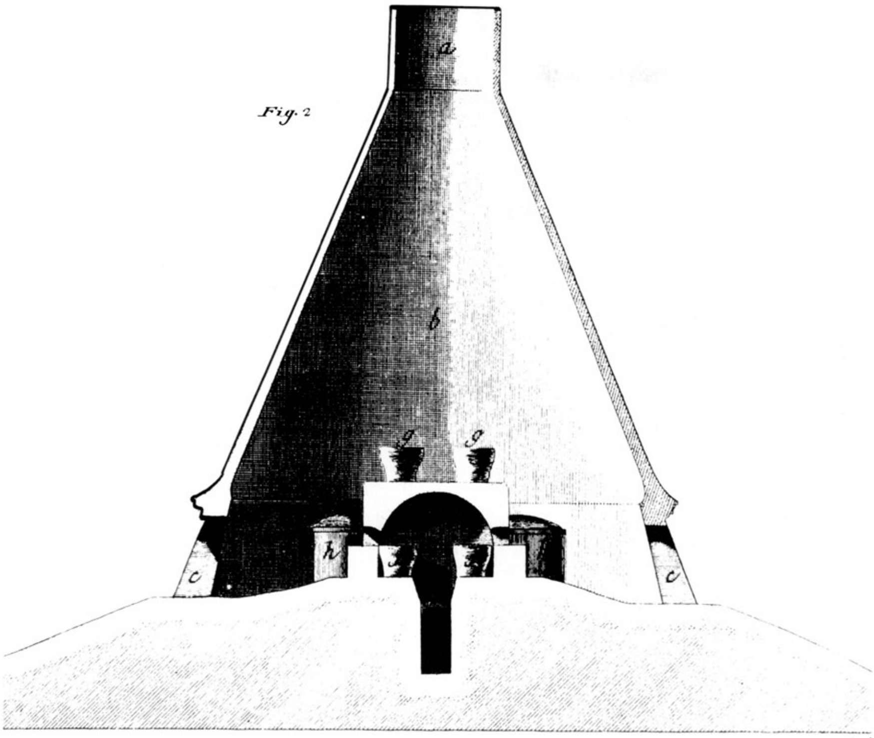
edges of the furnace, where the pots were placed. Around the base of the cone annealing ovens were built, and pots were dried on the top of the furnace. Ovens around the furnace heated pots and melted their contents before they were placed within the fire itself. These conical glasshouses sometimes fell without warning, but they continued to be used in England through the eighteenth century and well into the nineteenth. The French made little use of the conical shape, probably because their forests lasted longer than those of England and the conversion to coal came much later.

All furnaces consumed great quantities of fuel, and early glasshouses were located in forests, because it was cheaper to bring sand and the other materials to the furnaces than to transport fuel. The hungry fires were fed by felling trees around a glasshouse, until the distance to fresh fuel became so great that it was time to rebuild the furnaces in another part of the forest.

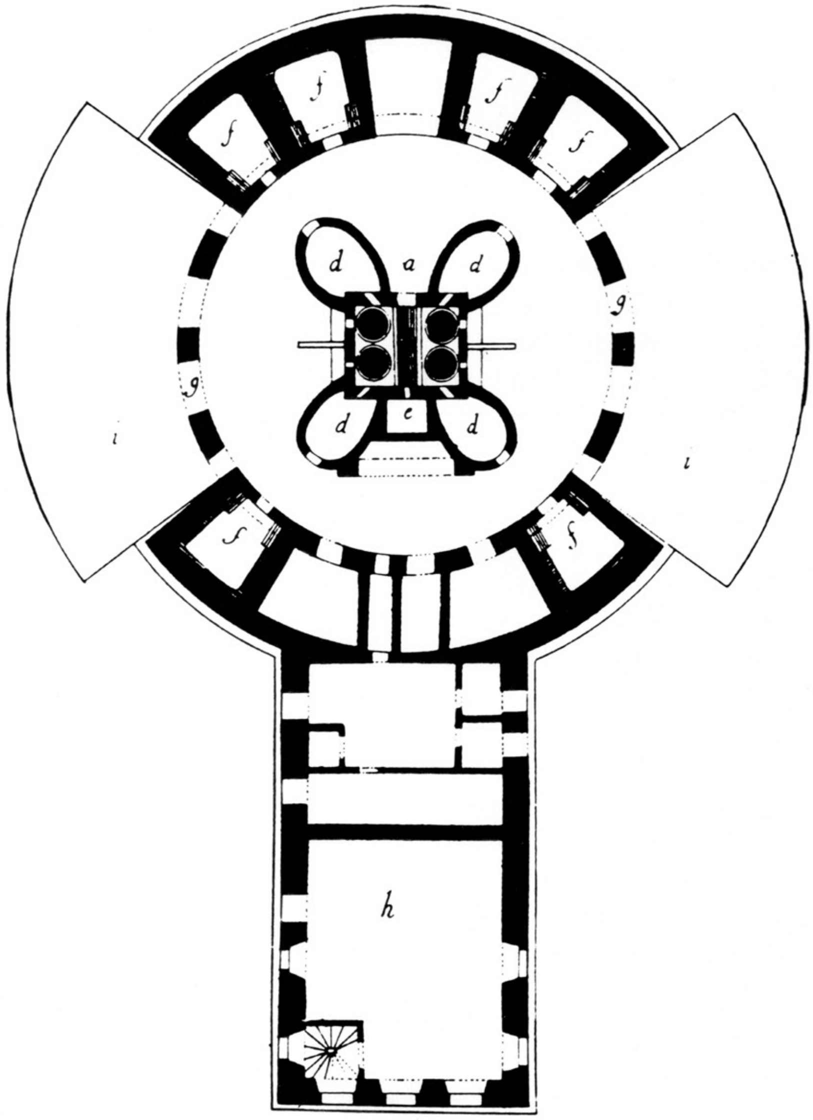
The earliest precautions against deforestation were the result of glassmakers' and ironmakers' denuding vast areas of ancient woodland. By the last years of Elizabeth I there was a remarkable increase in the use of wood to build ships and extend England's trade and to house a growing population. Consequently, the prices of firewood rose dramatically. The "Proclamation Touching Glasses," issued by James I in 1615, forbade the use of English timber by glassmakers. Experiments were made to substitute coal as a fuel in glassmaking and iron smelting, the latter a much larger industry. Smoke from coal colored the glass that was melted in open pots, and in covered pots it took longer and required more fuel to melt the batch. For some types of glass, such as that used in bottles, coal was soon adopted in England, but many manufacturers of window and plate glass continued to use wood until the middle of the eighteenth century.

France, with its broader areas of wooded land, waited well into the nineteenth century before a shortage of wood forced the adoption of coal as a fuel for glassmaking. As late as 1829, the Manufacture Royal des Glaces at St. Gobain melted glass with coal but used a wood-fired furnace for fining, the process in which bubbles were eliminated by stirring glass at high temperature and low viscosity.[24]

The use of coal put an end to small glassworks situated in forests, and the



5.11 The dramatic silhouettes of English cone furnaces were frequently seen along the canals and railroads of the eighteenth and nineteenth centuries. A chimney in itself, this form of glasshouse afforded the strong draft required by the use of coal as fuel. (Nineteenth-century engraving. Courtesy of School of Materials, University of Sheffield.)



5.12 A working furnace stood in the center of the English cone furnace, and air reached the fire through an underground tunnel. Ancillary spaces were often attached to the simple form of the furnace, providing storage for materials and rooms in which the business of the glassmaker might be transacted. (Diderot, *Encyclopédie*, 1762–1777, "Verrerie anglaise," plates 2, 3.)

industry's locations came to be more commonly determined by the availability of coal and access to shipping. In the United States the area of Pittsburgh and the Monongahela River became a center of glass manufacturing, with window glass almost half of the area's glass production during the nineteenth century.[25] Even when timber or bituminous coal was close at hand, in the middle of the nineteenth century a typical window glass plant paid more for fuel than for any other material used, about one-sixth of the total cost of ingredients.

Table 5.1 Various Compositions of Glass

	Sand	Lime	Soda
1880 (U.S.)	**73%**	**13%**	**13%**
1892 (Austria)	**68.5**	**10.5**	**21.5**
1925 (U.K.)	**72–74**	**12–14**	**12–14**

Window glass is made principally of sand, lime, soda, and other materials that usually amount to less than 1 percent of the mixture. Chemical analyses vary, but not greatly (table 5.1).[26] Sea and river sand were early employed in glassmaking, and where good sand was not available, ground flint and quartz might be used. Much of the sand used for glass, including France's famous Fontainebleau sand, was obtained by grinding quarried sandstone. Where local material was not satisfactory, sand was imported for making glass of the best quality. For plate glass some English manufacturers obtained Belgian sand, and German glassmakers long employed French sand.

A major early source of the soda needed for glassmaking was the ashes of kelp or plants growing at the shore. The French government offered a prize for the invention of a method for making soda from salt, and Nicolas LeBlanc won the prize in 1792. His process simplified the manufacture of soap, a major step in the improvement of public health, and provided soda for glassmaking. Toward the end of the nineteenth century a Belgian chemist, Ernest Solvay, introduced a method of producing soda from the ammonia by-products of manufacturing illuminating gas. The Solvay process produced a less expensive soda that soon replaced LeBlanc soda, which had often contained impurities that colored glass.[27]

Lime, a necessary ingredient to harden window glass and protect it from weathering, was to be found in most regions. In some locales, lime was prepared from mollusk shells, a method that had been used since Roman times. Every batch of glass also included cullet, waste glass resulting from breakage in the glassworks and from cutting sheets to size. Cullet took advantage of waste and sped the melting of the materials.

A greenish color resulted from the presence of iron in sand, but when manganese was used to counteract it the glass tended to acquire a purplish tone. Arsenic was often used to bleach the glass, eliminating the greenish cast of the cheapest kinds. The addition of magnesia assisted in controlling the viscosity of molten glass. A slight excess of manganese lent a pink cast to the glass, a shade that was briefly popular in the United States because the tinted light that fell through those windows was thought to be flattering to women.

A major expense of the glassmaker was preparing the pots in which glass was melted, costly when the pots proved to be sound, even more costly when they failed. Henry Chance described the problem in 1856:

> It was truly remarked to a manufacturer, at a period when such calamities were frequent, "Your pots break, because they break."

> The breakage of a pot often disturbs the furnace to such an extent, that the breakage of others follows, and many weeks will sometimes elapse before the disorganization thus produced can be rectified. The loss of the pot and the "metal" contained, is nothing as compared with the injury which the glass in surviving pots, and these pots themselves, are apt to sustain.[28]

At that time the average useful life of a pot was considered to be seven weeks. Later in the United States a pot, when fired with coal, was expected on the average to last four months, and a major advantage of the control available when firing with natural gas was the fact that pots might even survive six months of use. Since it required several months to prepare a pot for the furnace, the manufacture of pots was a significant part of the manufacture of glass.

Pot clay was carefully chosen. Each European nation had its own most respected clay, and in the United States before World War I more than half the clay was imported from Germany, until the cessation of imports led to the development of American clays.[29] As late as 1887, clay would be soaked for months before a barefoot workman trampled it into a smooth mixture without air bubbles. Over a period of almost six weeks the pot was built up until it was almost 3 feet high and 3½ feet wide at the top, with the walls of the vessel between 3 and 4 inches thick. The pot was fired after drying for four to eight months, and the inside surface was glazed with molten glass. The period between mining the clay and finishing the pot might easily total three or four years.

* * *

During the seventeenth and eighteenth centuries, glass and windows were still viewed as luxuries, and as such governments found them attractive sources of revenue. The English government, searching for means to finance the battles of William III, in 1690 imposed taxes on both glass and windows. The glass tax was discontinued nine years later, but the window tax remained until 1851, when it was replaced by a tax on inhabited house.[30] Factories, warehouses, commercial buildings, and empty houses were exempted from the window tax, and the number of taxable windows in a residence (the number above ten in a dwelling after 1747, and above seven after 1766) determined the tax, which was paid by tenants rather than their landlords. Between 1776 and 1808 the tax on a house with ten windows grew sevenfold, and often some window openings in large houses were filled with brick in order to reduce taxes. It was estimated then that, as a result of the window tax, English houses had half as many windows as were present in comparable European houses.[31]

The English tax on glass was reinstated in 1746, and it applied to imported glass as well as the output of English manufacturers. Because it was levied by the weight of glass produced, this tax encouraged continuation of the manufacture of crown glass, which was thinner than cylinder glass. The tax was calculated on the weight of entire disks of crown glass, but even after the inherent waste of cutting panes of crown glass there remained an economic advantage. Later a rebate of one-third of tax charges, based on the amount of waste in cutting crown glass, was also granted for cylinder glass, although there was little waste in cutting it. Thus the rebate was, in effect, a reduction of tax for cylinder glass, and this financial incentive persuaded many manufacturers to shift from crown glass to cylinder glass.[32]

The English tax on glass was high, often equal to half the cost of production and once going as high as three times the cost. In 1777, when funds were needed to fight the American Revolution, the glass tax was doubled, and another major increase took place in 1812, during the costly Napoleonic Wars. The English building boom of the 1820s, which stirred a large increase in the production of window glass, was fostered by the window tax being lowered by half and the permitted number of untaxed windows being increased.

English glassmakers opposed the window tax much more strongly than they opposed the tax on glass itself. Repeal of the tax on glass would have exposed English glassmakers to competition with foreign sources. But it was the tax on glass that was repealed in 1845, probably because it produced less than a fourth as much revenue as the window tax. Prices of window glass fell by more than half, and at the same time sales were greatly increased by the orders of London builders who were hurriedly completing buildings in the months before the Building Act of 1845 imposed new regulations on construction. For this greatly increased level of glass production there were too few qualified workmen, a shortage that forced Belgian manufacturers to raise the wages of their workers in order to prevent their leaving for jobs in England.[33]

In the United States cheap fuel was available, but that advantage was outweighed by high wages. A box of window glass made in England often cost two-thirds the price of an equal quantity produced in the United States.[34] Protective tariffs began in 1820, and imported window glass became an even smaller portion of consumption in the United States, dropping to about 2 percent around 1830. Under strong tariff protection until 1846, the window glass industry improved in the number and qualifications of workers available, but procedures were little improved. Then tariffs on glass were lowered to 20 percent, and duties continued low until the Civil War, when high tariffs on imported window glass were a means of increasing government revenues. Until the tariff act of 1913 brought about a drastic reduction of duties on window glass, U.S. industry worked under distinct advantages. Imports still came from Belgium, particularly in the small sizes of panes that were least profitable for American manufacturers.

At the end of the nineteenth century, prices for window glass in the United States were largely determined by prices of competing imports. Along the seacoasts, prices for domestic window glass were low in order to compete with the imports that arrived there. Railroad charges for transporting imports increased the price of imports inland, and prices for domestic glass increased accordingly, although the glass factories might be close at hand. For instance, the price of window glass in Pittsburgh, then a center of glass production, was appreciably higher than in Boston or Philadelphia. Protection was so thorough that in a two-year period of the 1890s manufacturers' profits tripled, although at the time the wages of glassworkers in the United States were two to four times those of foreign workers.[35]

After World War I, the reduction of tariffs produced sharp competition with European manufacturers, particularly those in Belgium. Foreign producers mechanized their production, matching the improvements made in the United States. Transatlantic shipping costs were so low, in comparison with rail charges, that in major American ports the shipping costs for Belgian glass could be lower than the cost of bringing glass from certain American centers of domestic production.

By the 1880s the unions that had been established by blowers, gatherers, cutters, and flatteners in the American glass industry joined the national organization of the Knights of Labor. The aggressive stance of glassworkers is apparent in their affiliation with this militant group rather than with the craft union of the American Federation of Labor.[36] At the same time, the American Window Glass Manufacturers Association was formed. The Association established price schedules, determined production quotas for all member plants, and negotiated with the union for all member companies. For over 20 years, the bilateral monopoly of these two organizations, management and labor, controlled most of the glass industry in the United States. In time, this comfortable relationship was threatened, principally by the manufacturing organization's being unable to control its members. During the 1890s about 20 of the largest window glass producers merged into the American Window Glass Company, which developed the Lubbers system of mechanically blowing cylinder glass and thereby eliminated many of its competitors.[37] Prices of window glass were elevated, but because window glass was so small a part of building costs, price increases as high as 50 percent did not cause a significant reduction of purchases.

The remaining independent companies in 1909 formed their own selling organization, but when it merged with the American Window Glass Company the combination was dissolved under anti-trust laws. Introduction of the Fourcault and Libbey-Owens methods of drawing sheet glass broke the tyranny of the American Window Glass Company, which had been largely based on its control of the Lubbers patents. Charges of violating anti-trust laws and conspiring to restrain trade were leveled at both the unions and the manufacturers. Most of the problems arose as a result of the industry's extremely rapid conversion from handcraft methods to mechanization, which made it possible to produce window glass at half the cost and eliminated the jobs of many highly trained craftsmen.[38] With self-imposed limits placed on the amount of glass that plants could produce, their operation had become so unprofitable that in 1922 one-seventh of American window glass factories did not plan to operate the next year.

Monopolistic maneuvers were not limited to the United States. American investors in 1902 explored the possibility of purchasing all of the Belgian glass factories, which were then supplying around 80 percent of American imports of window glass. Shortly thereafter Belgian manufacturers organized a glass trust, and all but one agreed to "the determinations of a committee with reference to selling prices, purchasing raw materials, and fixing wages."[39]

There was an old saying that three generations were necessary to make a glassblower, the elite of the glassworkers. The wages paid blowers were usually "higher than those for almost any other class of labor."[40] In fact, the owner of one American glass factory expressed the opinion that many glassblowers lived at a level of comfort rivaling that of their employers. An 1880 report on Belgian workers describes them as "well housed and well fed. . . . Among the dwellings of the well-to-do, the finest buildings belong to them. The blower is part of that class of workers who, by reason of their high salaries and the comfortable situation in which they find themselves, have acquired good manners and a degree of education."[41] The same report described their physical condition:

> They are usually large or at least almost always exceed the average; even the young apprentice blowers, called *gamins,* are distinguished by their height from other workers of that age and they carry the stigmata of their profession on their cheekbones, the tip of the nose, the chin, or the forehead.
>
> The heat of the fire, which they go very near to, has reddened those parts of the face that protrude. . . .
>
> The walk of the blower is remarkable. He walks with arms held away from his body; a position due to the large muscles in his arms and particularly in his shoulders. At the same time he gives a characteristic swing to his body, which reminds one of the swing he gives to the cylinder of glass.[42]

Emphysema, neuralgia, tuberculosis, and cataracts were foremost among the common maladies of the blowers, none of them surprising in consideration of the environment in which they worked. Alcoholism was a common problem and, on the whole, glassblowers were said to age quickly and die young.

The U.S. Census of 1880 showed that in window glass factories, where blowing the cylinders that produced sheet glass required greater ability than any other major branch of the industry, the requirements of experience and skill were reflected in wages. Master blowers received the highest daily wages (averaging $5.47); flatteners, whose work to a great extent determined the quality of the product, received the next highest wage ($3.82); cutters, less important for cylinder glass than they had been for crown glass, received the third level of wages ($3.14); and gatherers, who usually aspired to become blowers, earned an average of $2.72.[43] These wages can be compared to the average wage of $3.90 for managers of glasshouses in which they worked.

Before the introduction of the continuous tank furnace, a blower's team could not start its work until the glass was melted, but the time that this would take could not be accurately predicted. Filling the pots and melting their contents usually took about 24 hours. Once the glass was ready, a boy was sent to inform the blower's team, day or night, to appear at the glasshouse and begin their work. It might take about 8 hours for the pots to be "worked out," and only four or five work periods could be fitted into the week. Belgian glassblowers of the nineteenth century followed a somewhat different schedule, reporting for four 12-hour periods during a week but never working on Sunday. Most of them lived on small farms some distance from the glasshouses that hired them, and their weekends were reserved for planting and harvesting. Scheduling production was even more difficult because glasshouses always closed during the summer months, when the heat of the furnaces was absolutely unbearable. By 1899 many glassworkers' unions in the United States were sufficiently strong to prohibit glassmaking in July or August and to stipulate limitations on the quantity of glass to be produced, the number of apprentices that would be accepted, and the hiring of foreigners in the factories.

* * *

"Little Ice Age" is a term often applied to the period from 1550 to 1850, when Europe was subject to harsh winters and brief cool summers. To capture precious warmth during the short growing seasons, the Dutch developed the greenhouse.[44] The extravagance of hothouse fruit was attractive to wealthy merchants, and during long gray winters warm plant-filled rooms were a welcome respite from dank interiors. The most wealthy built orangeries in which their displays of tubbed orange trees were less a horticultural pursuit than a backdrop for entertainment—the luxury of fine gardens being provided indoors for enjoyment in inclement weather.

Manor houses of Elizabethan England usually had included long many-windowed galleries providing a place for strolls that could not be taken in cold and wet gardens. The old slowly walked up and down the gallery, while an attendant read to them; children played their games; and ladies chatted as they promenaded back and forth, passing the idle hours required by their station. By the early part of the nineteenth century, conservatories became a requisite of upper-class housing. Attached to a house, these glass rooms brightened adjoining spaces and provided leafy retreats from formality. House plants came to be a popular decorative element in the last half of the nineteenth century, lending a romantic informality to any room. Among the English middleclass it was said that each £100 of a family's income was indicated by a leaf on the parlor aspidistra, a house plant that had little to recommend it except its ability to survive the fumes of gas lighting.[45]

Large public conservatories were built and attracted streams of visitors who chatted, sipped refreshments, and listened to music among the exotic plants. Probably the most successful of these was the Jardin d'Hiver, built in Paris in 1848. It encapsulated formal gardens and a picturesque *jardin anglais*, which could be viewed from galleries above. The structure was cross-shaped, 300 feet in one direction and 180 in the other, and the roof was well above the top of a Norfolk Island pine that stood 50 feet high.

The ultimate pleasure garden was the Crystal Palace, designed for the 1851 Great Exhibition of the Industry of All Nations.[46] As the first of a succession of iron-and-glass exposition structures, the Crystal Palace pioneered a vast scale of construction and relied heavily on the experience of its designer, Joseph Paxton, in erecting greenhouses for the horticultural enthusiasms of the Duke of Devonshire. Construction of the project demanded speed and technological ingenuity (figs. 5.13, 5.14). Charles Dickens described the commitment that was required:

> Two parties in London, relying on the accuracy and good faith of certain iron-masters, glass-workers in the provinces, and of one master carpenter in London, bound themselves for a certain sum of money, and in the course of four months, to cover eighteen acres of ground with a building upwards of a third of a mile long (1,851 feet—the exact date of the year) and some hundred and fifty feet broad. In order to do this, the glass-maker promised to supply, in the required time, nine hundred thousand square feet of glass (weighing more than four hundred tons) in separate panes, and these the largest that ever were made of sheet glass; each being forty-nine inches long. The iron-master passed his word in like manner, to cast in due time three thousand three hundred iron columns varying from fourteen feet and-a-half to twenty feet in length; thirty-four *miles* of guttering tube, to join every individual tube together, under the ground; two thousand two hundred and twenty-four girders; besides eleven

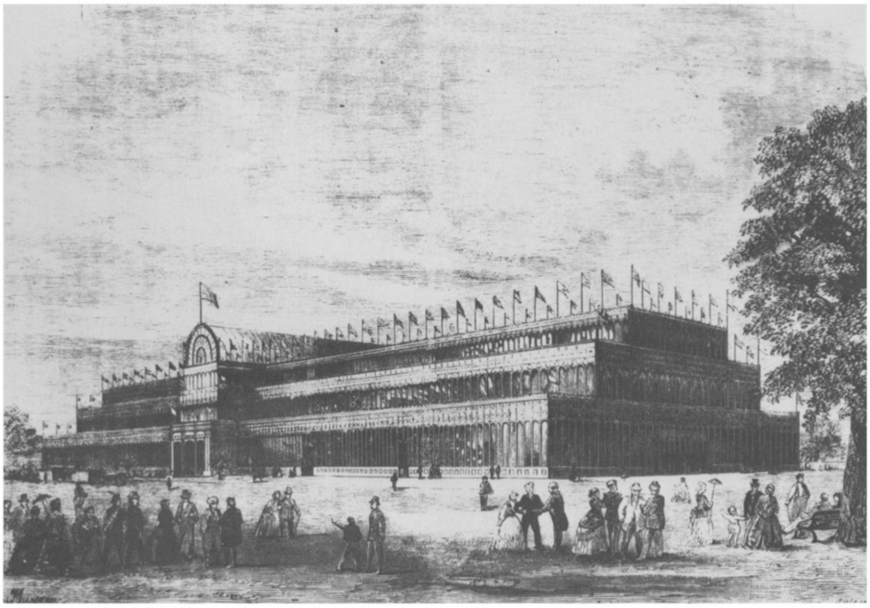
> hundred and twenty-eight bearers for supporting galleries. The carpenter undertook to get ready within the specific period two hundred and five *miles* of sash-bar; flooring for a building of thirty-three millions of cubic feet; besides enormous quantities of wooden walling, louvre work, and partition.[47]

The contract for glass was awarded to Chance Brothers and Company. A rival bid, only slightly higher, offered sheets 2½ times as large and over 1½ times as thick, made by rolling glass on a casting table. Although this glass might have offered greater protection from hail and would have required fewer wooden sash bars for mounting, its greater weight was feared. Chance Brothers supplied sheets 49 inches by 10 inches, produced by the cylinder process, three pieces being cut from each cylinder.

Lucas Chance owned a small glassworks, and in 1830 he and his partner had traveled to France to observe the production of cylinder glass at Georges Bontemp's factory outside Paris. Crown glass was favored in England, but the taxes on glass made it more profitable to manufacture cylinder glass. With blowers and flatteners sent by Bontemp, Chance began making cylinder glass in 1832. Production expanded, but the contract for the Crystal Palace required that in a few months they produce about twice the normal output of the five furnaces that were devoted to making cylinder glass. With the assistance of Bontemp, who had closed his Paris works following the Revolution of 1848 and joined Chance Brothers, additional workmen were recruited from France. Between August 1850 and February 1851 about 300,000 sheets of glass were provided for the Crystal Palace, and at the same time the company continued to fill its other orders.[48]

* * *

The efficiency of glass production was drastically advanced by improvements in furnaces. In the first decades of the nineteenth century, much attention had been given to achieving a scientific understanding of heat, a study fostered and financed by the opportunities for immediate application in



5.13 The Crystal Palace covered 17.5 acres of London's Hyde Park and enveloped full-grown trees. Prefabricated members of iron and wood supported the structure, and glass enclosed it. This was the largest order of glass that had ever been filled by a glass manufacturer, and much of it had to be replaced when it was broken by workmen rushing to complete the building within the scheduled time of 17 weeks. (E. Walford, *Old and New London*, 1872–1878, vol. 5.)

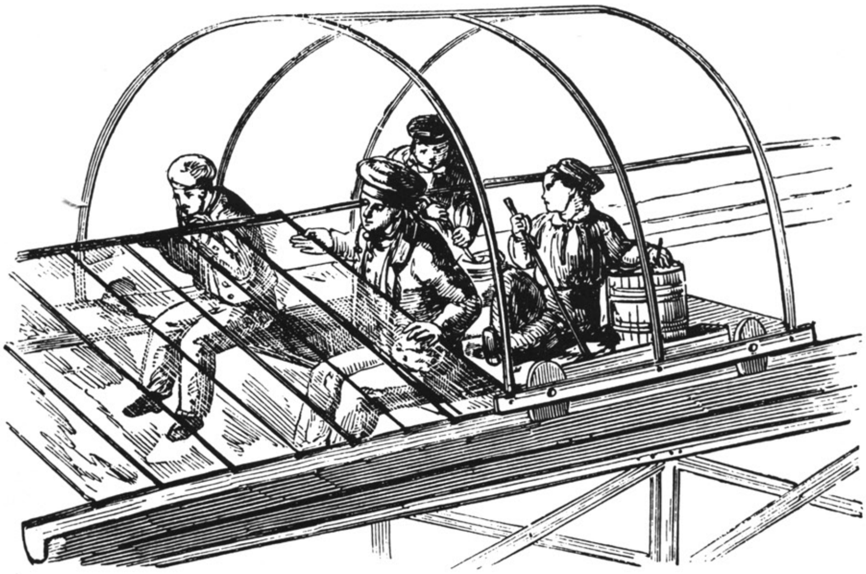
5.14 The glazing wagon that sped the roofing of the Crystal Palace rolled on wheels placed in the gutters that drained the roof. With so much glass to set in place, little effort was wasted. In fact, a worker set an average of 108 panes in a single day. The wagon had arched members overhead for canvas to protect the workmen, so that work need not be interrupted during the short construction period in the fall and winter of 1850–1851. (*Illustrated London News*, 7 December 1850.)

steam engines and smelting. At that time the accepted theory of heat pictured it as a sort of invisible substance referred to as "caloric." With the foundation of the science of thermodynamics, a relationship could soon be made between heat and mechanical energy, and the mysteries of steam and furnaces began to be unraveled. Frederick Siemens in 1856 patented a regenerative furnace, one in which entering air was heated by waste gases. Beneath the furnace two tunnels were built with grilles of firebrick across them. Hot gases left the fire through one of the tunnels, and fresh air entered through the other tunnel. When the walls of the tunnel exhausting gases reached a high temperature, a damper switched the direction of air flow. Entering air was then warmed by the masonry surfaces of the heated tunnel, while escaping heat raised the temperature of the cooler tunnel (fig. 5.15). This system required about half as much fuel as previous furnaces.

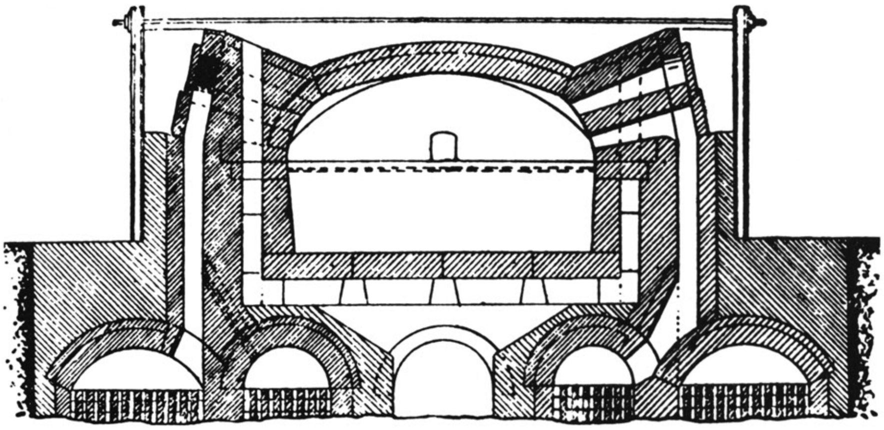
With the use of natural gas or producer gas, flames could be directed at the top of a tank furnace. In the "day tank" a batch of material was processed much as in a pot furnace: melted, refined, and then cooled to a viscous state. This work was done at night and a tank of molten glass was ready for blowers at the start of their workday. As with any furnace or kiln that is heated intermittently, a large part of the fuel used in a "day tank" was actually expended on warming the mass of the furnace, rather than in melting glass.

A tank furnace for continuous operation was soon developed. The first segment of the tank was used to melt materials with the heat of gas flames overhead. A dividing wall between the first and second chambers allowed melted glass from the bottom of the first chamber to flow into the top of the second chamber, where it was refined by being heated to a higher temperature at which bubbles and impurities would rise to the top. After it passed another dividing wall, glass in the third chamber cooled to the viscosity required for blowing.

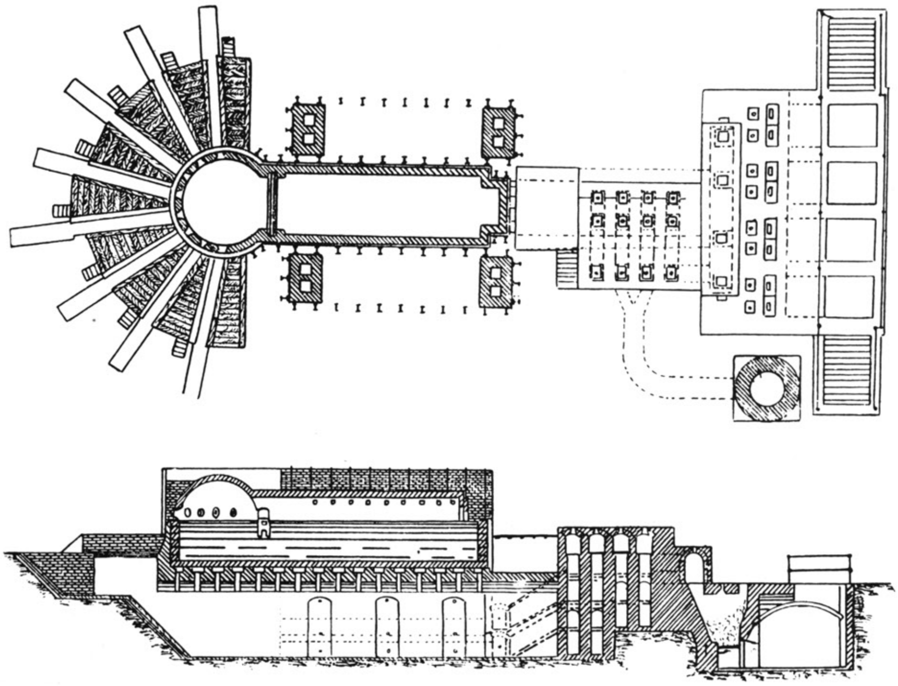
The tank furnace used for glassmaking, with gas heat from the top, was essentially the same as the open-hearth furnace used for making steel, and as the glass moved from one end of the tank to the other, it passed through all the traditional stages of preparation. Early tanks kept molten glass only about 10 inches deep. By 1879 that depth was almost doubled,



5.15 Air passages around the Siemens Continuous Tank-Furnace prevented temperatures that might damage the tank's walls. Tunnels beneath the furnace preheated entering air and expelled hot fumes from the fires. The tank itself (center of drawing) was divided into three sections. In the first, materials inserted through a door at the rear were melted; in the second, heat was raised and the material refined; and glass was drawn from the third, which was cooler. This continuous tank furnace used in glassmaking closely resembles the open-hearth furnace used in steelmaking. (*Appleton's Cyclopedia,* 1897, supplemental volume.)



5.16 Before the introduction of mechanized glassblowing, the continuous-tank furnace was highly developed. In this Belgian furnace the tank was fed from the right, and the prepared glass was kept in a circular portion of the tank, from which the platforms and trenches for eight blowers radiated. During a day of continuous operation, 24 blowers manned the furnace. (*Engineering Magazine,* November 1898.)



and in a Belgian furnace about 6 feet deep the glass almost solidified at the bottom of the tank. In practice, usually only about a twelfth of a tank's capacity was used in a 24-hour period, and each of the "working holes" at the end of the tank could be manned by a daily schedule of three shifts of blowers.[49]

The advantages of continuous tank furnaces fired by regenerative systems were many (fig. 5.16). By 1880, less than two decades after its first trials, the advantages of the continuous tank were spelled out in a U. S. Census report on the manufacture of glass:

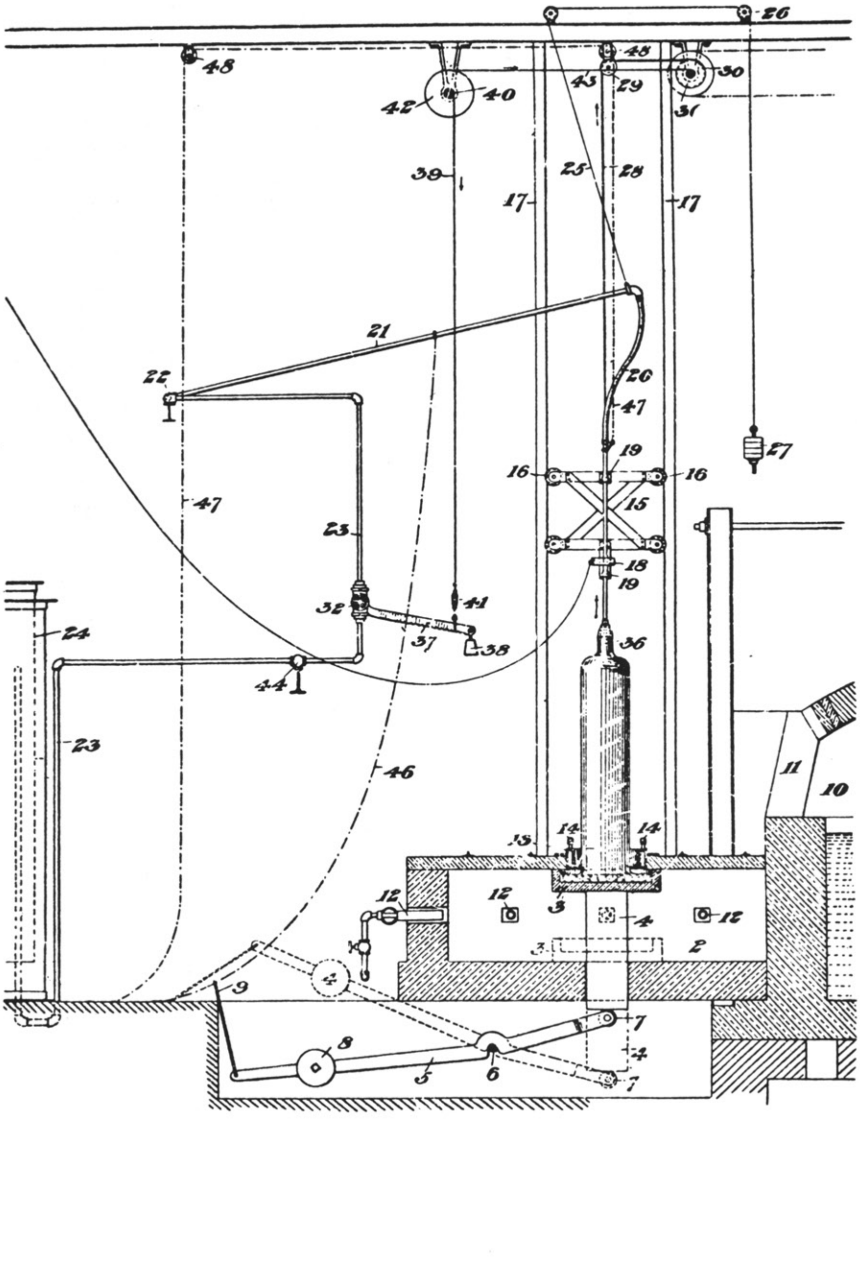
> 1. Increased power of production, as the full melting heat may be employed without interruption, while with the old method of melting nearly one-half of the time is lost by cooling and settling the metal, the working out of the glass, and the reheating of the furnace.
> 2. Economy in working, as only one-half the number of men are required for the melting operations.
> 3. Durability of the furnaces, owing to the uniform temperature to which they are subjected.
> 4. Regularity of working and improved quality of the glass made.
> 5. Convenience to the men and advantage to the manufacturers, as owing to the continuous action the metal is always ready for the blowers, and the gatherers can draw the metal from a practically constant level.
> 6. For the manufacture of window glass the working-out end of the furnace may be so arranged that the blowers can work without interfering with the gatherers.[50]

Near the end of the nineteenth century, a Belgian continuous tank furnace served as many as 45 blowers, 15 in each shift. In the United States, where introduction of the continuous tank furnace had been closely associated with the shift to natural gas as fuel, this was a common capacity and some furnaces had the space for 20 blowers at a time, arranged around the circular end of the tank.

The glass industry had long needed a fuel that could provide high temperatures with little contaminating residue. Producer gas first offered these advantages. To provide this gas, coal was burned in a sealed container separate from the furnace. When air and steam were passed through the thick layer of glowing coals, the gas obtained usually contained about 80 percent of the energy in the coal, roughly double the energy obtained in making coal gas.[51] Manufactured gas had obvious advantages, especially if the gas producers were located near the glass furnace so that the initial heat of the gas was not diminished. The combination of producer gas and the regenerative furnace was quickly adopted in Europe, particularly in England and France, but few were installed in the United States because their construction was costly, and the low price of fuel in America did not demand stringent economy in its use. Producer gas required shutting down weekly to clean soot from the chimneys, and many European manufacturers later converted their plants to the use of fuel oil.

French and Belgian glass had long excelled in quality, largely because of those countries' artisans' superior skill in filling and firing furnaces, but the discovery of vast deposits of natural gas in the United States gave the latter a great advantage. Manufacturers in the United States were persuaded to move their plants to areas where natural gas had been found. During the 1880s, the first decade in which natural gas was used, the number of glass factories in Ohio and the value of their output more than tripled. In Indiana during the same period, the number of glass factories rose from

5.17 In the Lubbers glass-blowing machine, air was fed through a blowpipe that moved vertically (21), drawing with it a measured quantity of glass that had been ladled into a heated vessel (3). Success of the process depended largely on regulating even movement of the blowpipe and stable air pressure. (U.S. Patent no. 702,013.)



four to 21, and the state's production almost quadrupled.[52] As the gas supply decreased in the Pittsburgh area, towns in Ohio and Indiana lured glassworks by offering cash incentives and free land for the construction of the factories. Edward Libbey, faced with labor problems and the high price of coal in Massachusetts, moved his entire plant to Toledo, Ohio, when civic leaders offered a free factory site. Unfortunately, before the introduction of welded steel pipelines in the 1930s, a local supply of natural gas might soon be exhausted, leaving glasshouses and other furnace industries without the fuel that had been the reason they came there. When natural gas was found in Indiana many Pittsburgh manufacturers moved there, but when these supplies of natural gas had been consumed, some returned to the Pittsburgh area, some transferred to Kansas and other new gas fields, and those remaining in Indiana converted their factories to make producer gas from coal.

European countries, not having extensive deposits of natural gas, relied on coal and oil. In the United Kingdom, from 1950 to 1965, the amount of coal used in glass production dropped drastically and the amount of oil used increased more than fourfold. The use of electricity grew in regions that were rich in hydroelectric power, but usually it served only as a supplement to other fuels.[53]

* * *

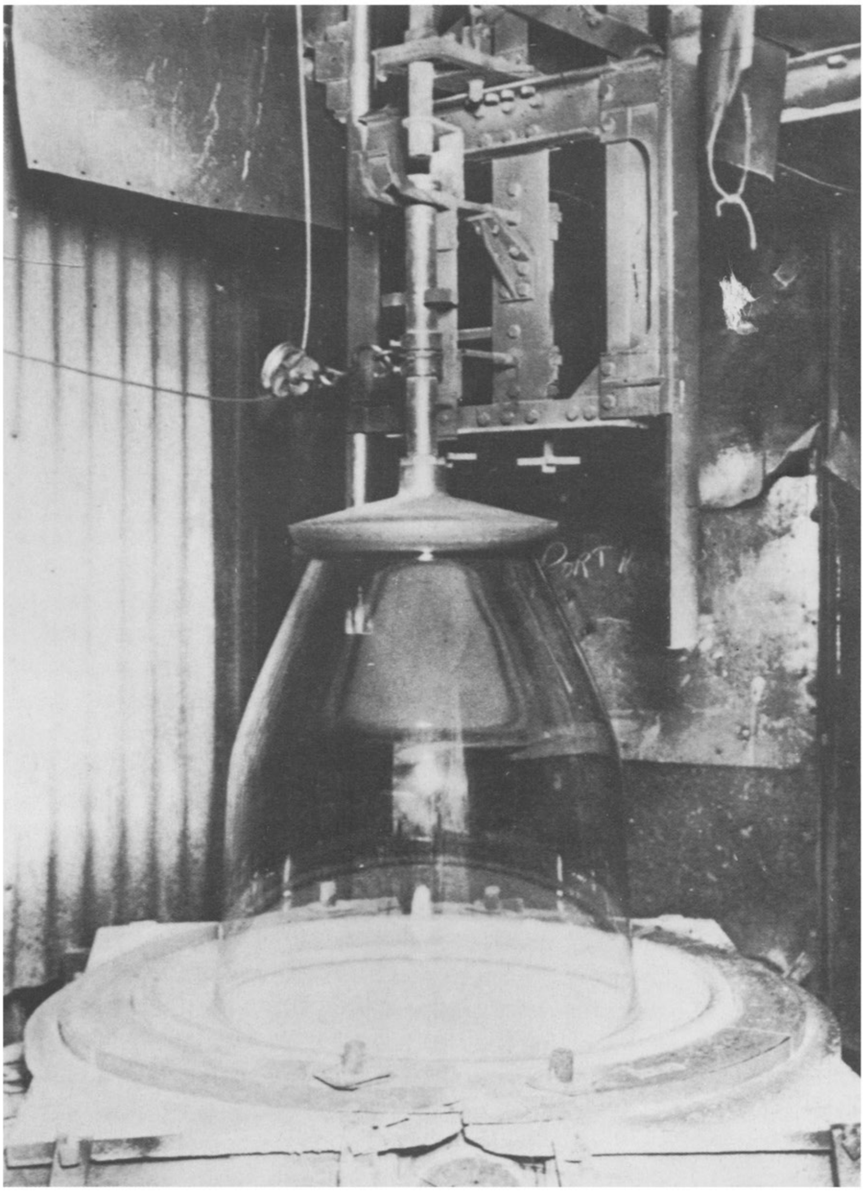
During the last half of the nineteenth century there were repeated attempts to invent machines that could replace the glassblower in the production of both cylinder glass and bottles. Compressed air and measured quantities of molten glass were employed to control the blowing process for making bottles, but mechanically imitating the deft movements of the glassblower who made window glass was much more difficult. In 1896 John H. Lubbers, a flattener working at a South Pittsburgh window glass factory, began experiments on the use of compressed air to blow cylinder glass, working with the support of his employer and a group of investors.[54] By 1903 the English company of Pilkington Brothers was considering investment in the Lubbers process, but officials of the concern received a report advising against negotiating with Lubbers (characterized as "a clever man but generally drunk"), because the system was not yet developed to the point of practical application.[55] In the same year, Lubbers's patents were purchased by the American Window Glass Company, which controlled some 85 percent of the U.S. industry's output. By 1911 around half of American window glass was produced by machines. The manager of a plant in the United States explained the popularity of the process: "The machines make poor glass . . . but they make so much more glass that they can pick out a great deal of good glass and sort it very carefully."[56]

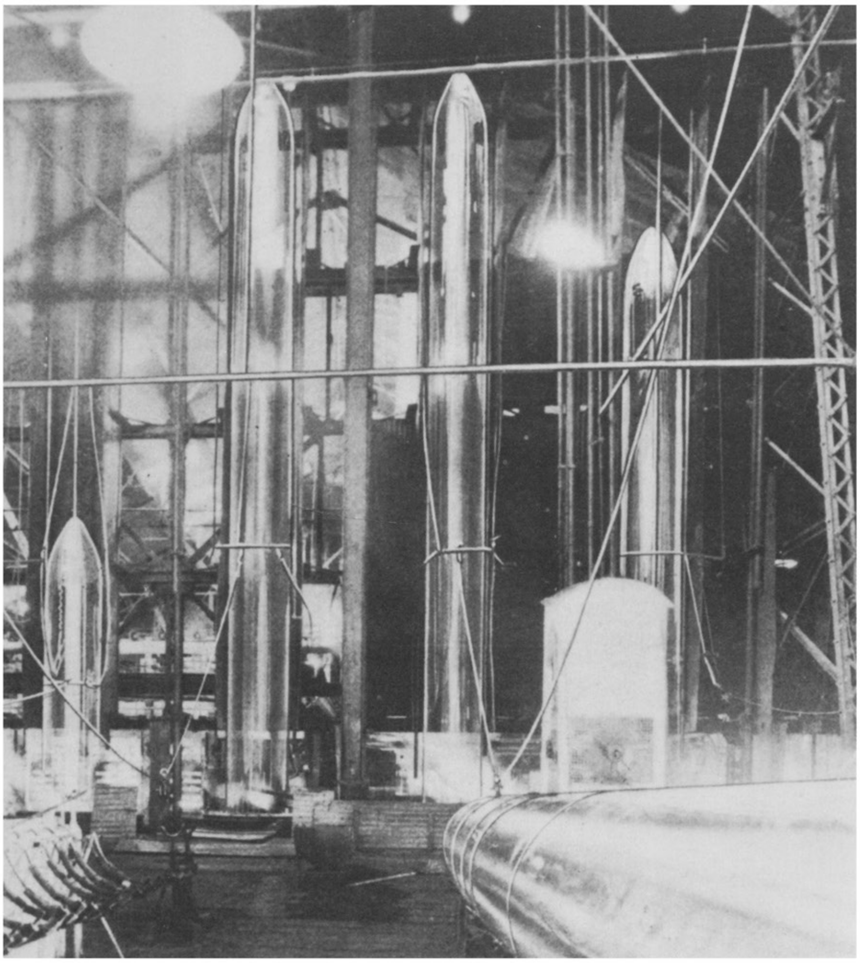
In the Lubbers process, refined glass was ladled into a large flat dish of fireclay, which was heated from beneath (figs. 5.17, 5.18). The flared head of a vertical blowpipe was lowered and held there until glass had solidified around a flange on the inside rim of the blowing head. As machinery raised the blowpipe, air pressure enlarged a bubble until it attained the circumference desired for the cylinder. Once formed, this shoulder dimension could be maintained if constant air pressure was maintained as the blow-

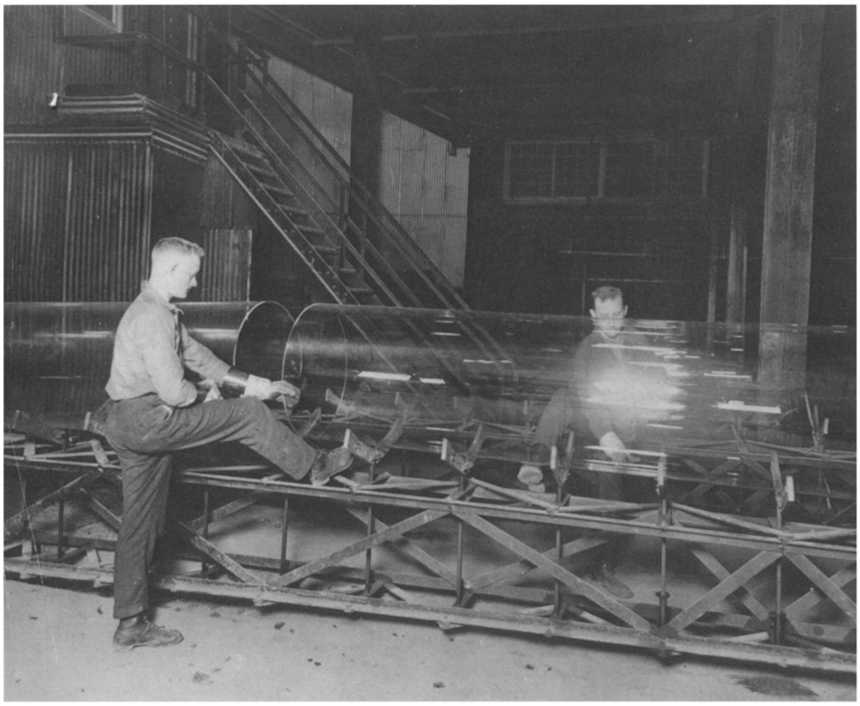
5.18 This critical phase of the Lubbers process determined the diameter of the cylinder to be blown by slowly lifting the blowpipe. Once this task had been completed, it was a simpler matter to raise the blowpipe while maintain a constant pressure within the cylinder. (Courtesy of Pilkington Brothers, Ltd.)

5.19 Cylinders completed by the Lubbers process lie near the area where cylinders are drawn. As they rose, cables were secured around the cylinders to prepare for the delicate work of lowering them to a horizontal position. (*Compressed Air Magazine*, July 1921.)

5.20 Once the Lubbers cylinders had been gently lowered, they were cut into several sections. These were then slit and taken to a flattening oven. From that point the procedures were the same as those used with hand-blown cylinders. (Courtesy of PPG Industries.)







5.21 After the introduction of the Lubbers method for mechanically blowing cylinders of window glass, there were many patents filed that described means by which the tall cylinders of glass might be safely lowered from their upright positions. Like L. R. Schmertz's patent, most depended on a system of cables and pulleys to swing the cylinder to a horizontal position, resting on a cradle. (U.S. Patent Office, Official Gazette, 9 July 1908, no. 890,306.)

pipe drew glass upward. A motor slowly raised the blowpipe, and so a tall cylinder was produced, cooling as it rose. When its full height had been attained, the cylinder was ended by rapidly lowering the dish of hot glass or speeding the vertical movement of the blowpipe until the walls of the cylinder drew thin and ended.

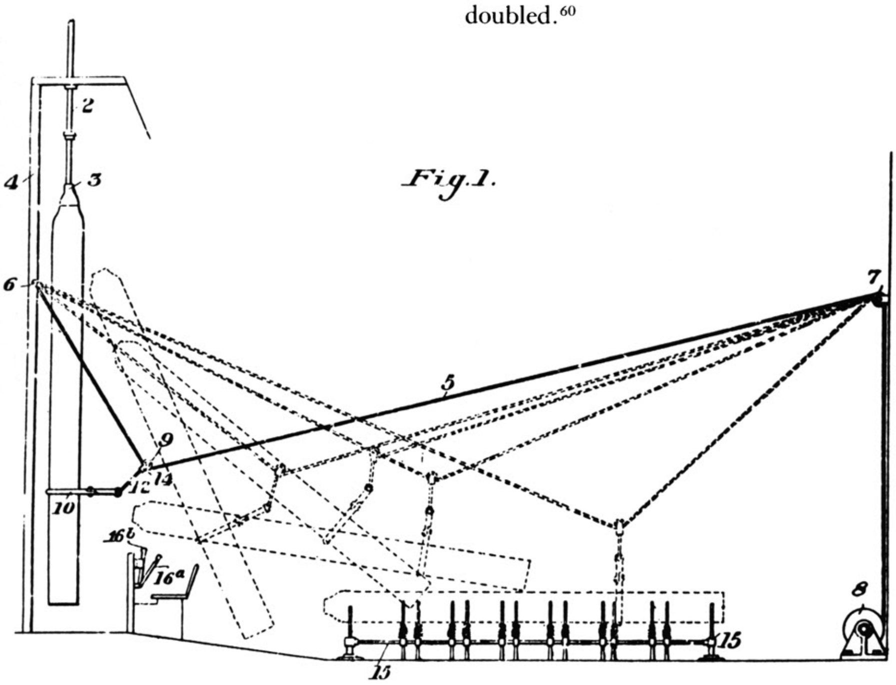
At first the Lubbers machine produced cylinders roughly 5 feet long and 1 foot in diameter, about the size of hand-blown cylinders. Since a large part of the time required to produce a Lubbers cylinder was absorbed in ladling a fresh supply of glass and starting the blowpipe's upward movement, there were obvious advantages in increasing the size of the cylinders blown. First, length was increased to around 25 feet, but the size was limited by the difficulty of flattening the glass as a single large sheet. Soon the diameter of cylinders was increased, and the long tubes of glass were cut into lengths that would be manageable in the flattening oven (figs. 5.19, 5.20). Eventually cylinders over 40 feet tall and more than 30 inches in diameter were produced. Before flattening, these cylinders were cut into 10 or more segments by wrapping a red-hot electric wire around the cylinder. Blowing a cylinder of single-strength glass required about 35 minutes, and double-strength about 50 minutes.[57]

The mechanical blowing of window glass was constantly endangered by drafts in the glasshouse, for if one side of a cylinder were even slightly cooler it would be drawn thicker throughout its entire height. Residue from a previous charge of molten glass could cause streaks in a cylinder, but this problem was soon solved by the introduction of a reversible container that could be flipped over, so that residue would drain away while a new charge was being ladled into the upper part. In early trials it was discovered that hand control of air pressure and the movement of the blowpipe did not satisfactorily govern the thickness of cylinder walls. An intricate system of automatic controls was developed to insure the variations of pressure and vertical speed necessary to produce a cylinder of uniform thickness.

Not the least of the problems in processing mechanically blown cylinders was that of lowering a tall vertical cylinder of glass to a horizontal position, where it could be divided and slit for the flattening process. U.S. patent records of the period show many inventions that used slings and cables to bring a cylinder as tall as 40 feet to the cradle on which it was to be divided (fig. 5.21).

Mechanically blown cylinders of window glass required that the relatively few workers needed be highly skilled and highly paid. Continuous tank furnaces were usually enlarged because a great amount of glass was required for the mechanical process. With as many as 12 machines operating around the clock from a single furnace, extraordinary amounts of glass could be produced. A French report indicated in 1926 that a single machine could manufacture around 2,000 square feet of window glass in a day.[58] It was the early 1930s before cylinder machines in the United Kingdom and the United States had been completely replaced by sheet drawing machines, which eliminated the flattening process, the flaw inherent in manufacturing cylinder glass, by hand or by machine.

In 1904 a French writer surveyed the whole of his country's glass industry for the *Revue des Deux Mondes:* "He did not find in it, as in so many other industries, that constant application of mechanical improvement in order to economize the human material at work. On the contrary, there seemed to him to have been but little progress in that respect since the days of the old Egyptians."[59] This comment preceded the vast changes that were made by mechanization of the production of window glass. Potmakers had been eliminated by the introduction of the continuous tank furnace. Blowers and gatherers were replaced as the Lubbers system of machine-blown cylinders came into use, and flatteners would no longer be needed with the advent of drawn glass. The workers no longer required were those who had been at the top of the wage scale. After mechanization, a union survey showed that of about 600 glassworkers recently laid off in the United States, roughly 100 remained unemployed and an equal number had obtained employment within the glass industry. The remainder, two-thirds of them, had found employment in other fields or operated their own small businesses, among which saloons and billiard parlors were most frequent.



Changes in the window glass industry can be seen in data regarding American production in 1899 and 1925, dates that include many of the changes mentioned above. During this period the 100 window glass factories in the United States were reduced to 42, while the total number of workers employed declined insignificantly and the output of glass more than doubled.[60]

Throughout the last half of the nineteenth century, many schemes were patented to draw flat sheets directly from a mass of molten glass. Cylinders had been successful because internal air pressure maintained the dimensions of the cylinder. If the cylinder was to be replaced by flat sheets, thus avoiding damage from flattening, it was necessary to find a method that would prevent the sheet's narrowing and thickening ("tailing off") as it was drawn. In addition, it was necessary to limit the contact of the soft ribbons of glass with parts of the machine that might mark its surface. A solution was discovered by Emile Gobbe, a Belgian glassmaker. By floating on viscous glass an open box-shaped vessel made of fireclay, a sheet could be drawn upward through a slit in the bottom of the clay *débiteuse*. As water rises in a leaky boat,

5.22 The Colburn patents for drawing sheet glass, like others, used a *bait* to start drawing the glass upward. The more difficult task was preventing the sheet of glass narrowing as it was drawn. This patent included the claim of "imparting movement to the surface portion of the molten mass away from the medial line of the sheet." For that purpose, two revolving elements are placed below the drawing level to pull the glass outward. (U.S. Patent no. 821,780.)

5.23 Early drawn glass was often marred by rough edges of the slit in the *débiteuse* through which it was drawn. In the Colburn system no slit was used. Two rollers moved the molten glass toward the point where the drawing was done. Immediately above these rollers the glass was cooled, to be reheated again (*B*) in order to bend to a horizontal direction. The band of glass moved forward onto rollers (C), and overhead sprocket chains (*F*) drove grips that pushed the sheet of glass along the production line. Obviously the timing of all phases of the machine had to be carefully synchronized to produce clear glass of a consistent thickness. (*Scientific American Supplement*, 16 May 1908.)

the weight of the fireclay forced a band of glass to rise and, so long as that glass was drawn upward at the same rate that it appeared, a continuous band of glass could be obtained. To start the flow of glass, a *bait*, usually a piece of glass or metal mesh, was inserted into the slit at the bottom of the *débiteuse*. Gobbe's invention was improved by Emile Fourcault, an engineer who had succeeded his father as director of one of Belgium's largest glassworks.[61] The process was patented in 1902 after several years of experimentation, but another decade remained before the Fourcault process, as it came to be known, was sufficiently developed to be placed in production. At a glasshouse in Dampremy, in the coal-mining region of southwest Belgium, a small tank furnace was built, and through a two-year period one, two, and three machines were tested. It was estimated that glass from this experimental plant cost about 40 percent less than that produced by the usual methods of the day.[62] The system's performance in tests was sufficiently favorable to lead the Fourcault-Frison company to install a large continuous tank furnace with eight machines to draw glass.

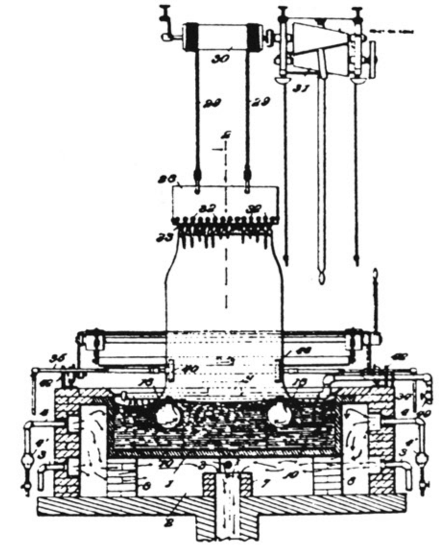
In the Fourcault system, once a bait of metal fabric started the flow, it was necessary to cool the sheet of glass before it would be touched by the rollers that drew it upward. For this purpose, water-cooled tubes were placed on either side of the glass a short distance above the *débiteuse*. These tubes lowered the temperature of the glass sufficiently to achieve a viscosity that prevented the band of glass narrowing and avoided its surfaces being marred by the asbestos-sheathed rollers that pulled it higher within an enclosed and insulated shaft. Fins inside this shaft, more than a dozen spaced about a foot apart, caught any broken glass before it fell into the tank, and the temperature of the drawn glass was gradually reduced as it moved upward. By this arrangement the use of an annealing oven to slowly cool the glass was eliminated. As the band of glass rose from the topmost rollers, some 30 feet above the tank, it was cut into lengths of about 6 feet, and these were taken to the cutting room where they were divided into panes of the desired size.

By incorporating the annealing process and eliminating flattening ovens, the Fourcault system conserved fuel and produced sheet glass with a clean, brilliant surface. More than two-thirds of labor costs present in the manufacture of handmade cylinders were eliminated.[63] Thickness could be accurately controlled by varying the speed at which sheets were drawn from the *débiteuse*. There were often long streaks produced by impurities in the mass of melted glass, but with experience these imperfections were reduced in number and size.

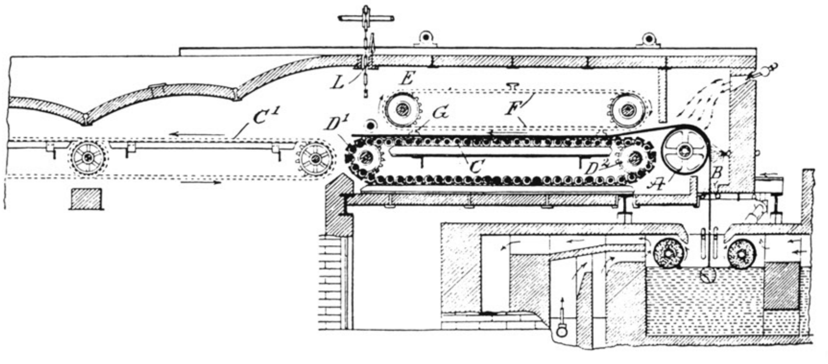
Unfortunately, large-scale production of drawn sheet glass began at Dampremy in 1914, the year that German troops invaded Belgium. It was 1919 before a Fourcault machine operated in England, and five years later there were only two Fourcault plants in the United States. Once the postwar building boom had subsided, hard times restrained the window glass industry's investments in new equipment.

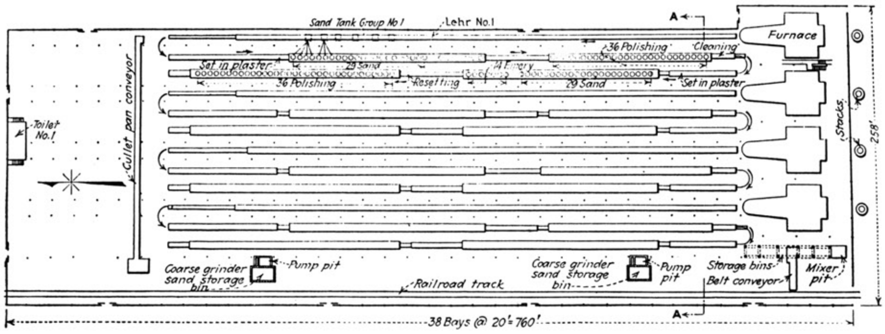
In 1898 Irving Colburn had started experiments in a small Pennsylvania community, trying to develop a machine that would blow lamp chimneys and drinking glasses. After two years Colburn shifted his attention to the development of an improved machine to blow cylinder glass, an unsuccessful project that lasted several years. In 1906, five years after the Fourcault patent, Colburn found investors and formed the Colburn Machine Glass Company, intent on discovering a way of drawing sheet glass (figs. 5.22, 5.23). A Colburn machine was sold but, after a well-publicized start, the machine failed in operation. Colburn continued experimenting until his company closed in 1911, and its patents were bought at auction by the Toledo Glass Company. Four years of development and testing in Toledo prepared the way for the formation of the Libbey-Owens Sheet Glass Company and the construction of a plant in Charleston, West Virginia, to start commercial production of window glass using the Libbey-Owens equipment, as it was then called.

Colburn's machine, as described in 1908, drew a sheet of glass directly from the surface of a shallow tank, the draw being started by a metal bait. To prevent the sheet narrowing as it was drawn, Colburn provided a rotating sphere of fireclay at each edge of the draw, pulling the glass outward as the sheet rose and was cooled. (Libby-Owens replaced this device with a pair of small ridged rollers.) By grasping the edges just before the glass had cooled, the width was maintained without making an imprint. Shields on either side of the rising band of glass protected it from the heat of the furnace. After being drawn about 8 feet upward, the glass was slightly softened by a row of glass flames and then rolled over a cylinder to a horizontal direction. A series of belts carried the band 200 feet to the cutting table, and on the way it was annealed. The bending roller, made of a nickel alloy, was air-cooled to maintain a faint red glow, for if the roller were too hot glass adhered and if too cool the surface of the glass would be marred.[64]



The speed of the Libby-Owens machinery varied according to the thickness of glass to be drawn. In 1925 thicknesses ranged from 1/24 to 5/16 inch, and speeds from 100 to 25 inches per minute. Savings in labor had been discovered in the 1908 tests, for which it was reported: "There are no gatherers, blowers, snappers, or flatteners. The cutters and superintendent are the only skilled men employed, and the cutters will some day give way to automatic devices. With three men and six boys more glass and better glass is made by the machine than can be made by thirty-nine men with the cylinder process."[65]





5.24 At Ford's River Rouge plant, each of the four furnaces (right) fed glass to a production line that extended the length of the building (about 1,500 feet) three times before the polished glass was ready for installation as automobile windshields. The first length was the annealing furnace, a journey of about three hours during which the temperature of the glass was controlled by gas jets. The second length ground and polished one side of the sheets of glass; and the third length completed the other side. (*Engineering News-Record*, 4 September 1924.)

"One tank furnace would feed four [drawing] machines, giving a daily output of around 250 tons so that the glass for the Crystal Palace would absorb approximately two days' production."[66] Nevertheless all problems had not been solved. The Fourcault system was troubled by deterioration of the slit through which glass was drawn. Glass made by the Libby-Owens system was often marred by contact with the bending roller, in which it was difficult to maintain the critical temperature. In the 1920s a new system was developed by the Pittsburgh Plate Glass Company, combining features of the two earlier systems. Glass was drawn from the tank much as in the Libby-Owens system, but it continued upward as in the Fourcault system. All three systems were in production in 1950, when Fourcault equipment was used for about 72 percent of the sheet glass produced world-wide, Colburn equipment for about 20 percent, and Pittsburgh Plate Glass systems for the remainder.

After the systems for mechanized production of window glass were developed, a new market for plate glass materialized. About 4 million automobiles were built in the United States during 1923, and roughly half of them—in fact, about half the automobiles driven anywhere in the world at that time—were Model T Fords produced by Henry Ford's assembly line methods. Ford had early encountered difficulty in obtaining an adequate supply of plate glass for the windshields of his automobiles. Since the start of the century the number of plants producing plate glass in the United States had not increased, though their output had almost tripled. The use of plate glass for store windows provided an ever-expanding market, and the increasing enclosure of automobiles promised to elevate the demand far beyond the industry's capacity. In response to these factors, prices for plate glass more than doubled in the United States, and imports increased.

In 1922 Durant Motors, Inc., bought the American Glass Company, and in 1926 the General Motors Corporation would buy the Rishers Brothers plant. Ford bought the Allegheny Plate Glass Company near Pittsburgh, but its output proved inadequate for his needs. At his Highland Park factory in Detroit, trials were made producing plate glass by a continuous process without grinding or polishing, but after two years of experimentation under inexperienced direction the project was abandoned, leaving behind a great mound of cullet that had been produced by the trials. A new start was made, acknowledging the need to grind and polish the material in the traditional manner, but nevertheless operating as a continuous process, the production system for which Henry Ford was famous. Once initial breakdowns had been repaired, the Highland Park plant produced plate glass at the rate of 1,250,000 square feet annually, but that was only 7 percent of the amount the Ford Motor Company required.[67]

A plate glass plant capable of producing 10 million square feet of glass per year, eight times as much as made by the Highland Park prototype, was built in 1924 at Ford's River Rouge plant (fig. 5.24). At one end of the building, four tank furnaces were fired by gas, and the escaping fumes heated the passages through which air was admitted to the flames. At each furnace a spout below the top level of the molten glass allowed a band of glass about 12 inches wide to flow out and continue between a pair of water-cooled rollers, which controlled the thickness of the ribbon and increased its breadth to 20½ inches. From the rollers the glass began its travel along a belt, through a gas-fired annealing tunnel oven 520 feet long, which in three hours gradually lowered the temperature of the glass from 1,150° F to about 80° F. At the end of the tunnel the glass was cut into pieces approximately 9 feet long, ready to start the nine-hour process of grinding and polishing both surfaces.[68]

As in the traditional manner of making plate glass, pieces were set in plaster. Chain-driven tables passed under 29 rotary grinders using successively finer sand and 14 grinders using emery or powdered garnet (fig. 5.25). Then the glass was rouge-polished by 36 felt-surfaced buffers. The sheets were stripped from the tables, turned, and once again set in plaster for the process to be repeated on their other surfaces. Remembering the dramatic moments of blowing window glass and casting sheets of plate glass, the periodical *Glass Worker* wistfully commented, "The spectacular has been eliminated."[69]

All of this process was little more than an ingenious conversion of traditional techniques to modern assembly line procedures in which the pieces of glass could be moved along at the rate of 35 inches per minute. At first as much as half the glass was lost due to breakage in the annealing and grinding processes, but in time losses were somewhat reduced. Broken sheets of glass were cut to make windows smaller than windshields.

As the continuous process was developed, it effected a saving of one-third in labor costs required to produce polished glass. However, by 1929 only half of American plate glass production came from plants using the continuous process. Since in that period three of the four continuous process glass plants were owned by automobile manufacturers, one must conclude that the continuous process dominated the manufacture of automobile glass, while most glass for storefronts was made by older methods.

The Ford process of making plate glass provided a system of continuous grinding and polishing, but it was necessary to set the sheets of glass in plaster and turn them by hand, a time-consuming task. The English firm of Pilkington Brothers initiated experiments on a truly continuous system that would simultaneously grind both sides of a band of glass, and in 1935 that machine was put in commercial operation. From the tank furnace, glass ran between two rollers. The sheet continued through an annealing oven, then between grinding disks above and below. At first the glass advanced at the speed of 45 inches per minute, but improvements soon attained a speed of 200 inches per minute.[70] The twin grinders were the source of most difficulties, and often it was necessary to cut the band

5.25 Water and sand from the River Rouge grinding machines ran into a channel in the factory floor and were pumped from there into a storage tank. At the tank, the sand was separated into seven sizes for reuse. In the same way, the emery particles used for finer grinding were graded into five sizes. (*Glass Industry*, January 1923.)

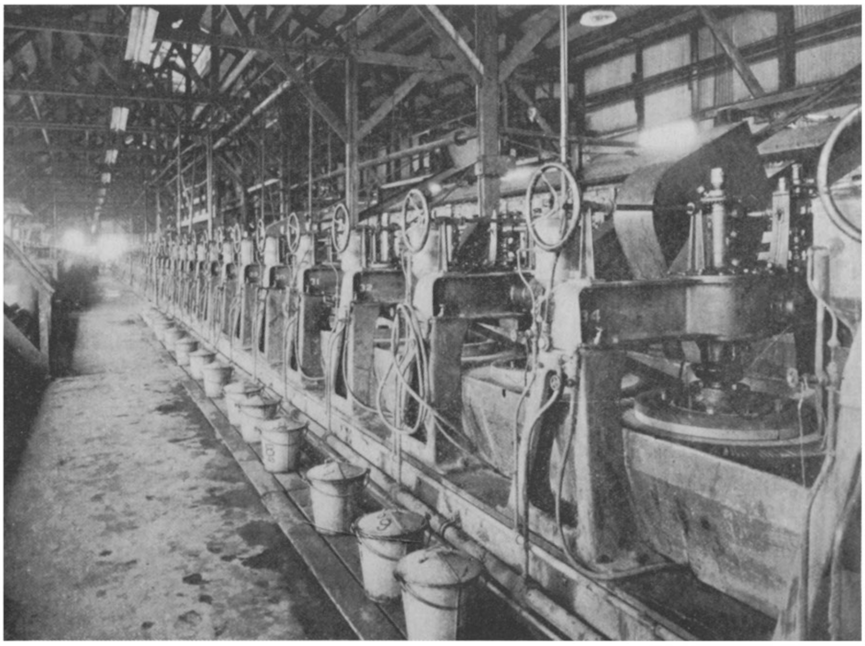
of glass into sheets and finish it in the manner of the Ford process.[71]

None of the processes developed for sheet or plate glass provided the "fire-finished" surface that had always been admired in crown glass. There were experiments that attempted to remelt the surface of the glass, but once the glass was again brought to a soft state it required support and any surface underneath was certain to leave some imprint.[72]

In 1952 Alastair Pilkington of the British firm of Pilkington Brothers Ltd. began experimentation on a process in which a vat of liquid metal was used to support the glass ribbon pouring from a tank furnace. By placing gas flames overhead and floating the glass on melted tin, heat could be applied to both the upper and lower surfaces, simultaneously achieving a "fire-finished" gloss on each side of the glass. Seven years were taken in developing the process to the level of commercial application. The complex chemistry of the interface between melted glass and melted tin required careful analysis and repeated experiments, and to prevent oxidation it was necessary that the tin and glass be brought together in a gas-filled chamber. At the end of the vat, the glass was cool enough to allow it to move off the surface of melted tin into an annealing oven without damage to its surfaces. A major advantage of float glass production was its speed. No longer controlled by the time-consuming operations of grinding and polishing, plate glass could move as fast as 45 feet per minute, about 16 times as fast as Ford's River Rouge plant. Furthermore, the high percentage of breakage, inherent in the grinding process, was eliminated.

* * *

Glass in architecture has traditionally been associated with the interruption of a solid wall or roof to provide vision and daylight, ventilation being more a function of the sash than of the glass. The use of large wall panels of glass was considerably advanced with the art of fashioning Gothic church windows, with the leading of the colored glass braced by iron bars, but the Crystal Palace and many of the exhibition buildings that followed had almost all their external surfaces, in some cases even the roof, covered with glass. From this came a new architectural expression, which one observer hailed as the "Ferro-vitreous Art" of the future.[73] With the introduction of skyscraper construction, supporting the walls of each story separately on the steel frame, exterior walls became nonsupporting, merely curtain walls—a term already in use at the time. With feeble gas lighting or even the first electric lights, it was necessary that windows in office buildings be large to take in enough light to fill the depth of offices. In some cases, the expanse of glass was interrupted by little more than the depth of floor beams and the width of columns. This was particularly seen in office buildings constructed on party-wall sites, where the front wall, and perhaps a skylight, had to provide almost all of the daylight within. In the Hallidie Building in San Francisco (1918), a wall of glass four stories high was placed approximately 3 feet in front of the floor beams, braced by concrete window sills less than 3 inches thick. Only eight years later the machine shop of the Bauhaus in Dessau sheathed three sides in glass set away from floors and columns. Transparency had become an architectural medium, challenging the solidity of past architecture; and, in a world that associated fresh air and sunlight with physical and spiritual health,



openness was festive. In a practical sense, tighter-fitting sashes and steam radiators allayed the chills and drafts that had always been associated with windows.

In addition to its transparency, glass afforded a clean, hard, smooth surface to withstand the fouled atmosphere of smoky cities, where soot settled on building surfaces to make pale tones of brick a dull gray and washed down walls to blacken the ground floors of buildings. In the 1930s an opaque colored glass facing was introduced by major manufacturers. Available in rich colors ranging from white to black, sheets of this material could be attached to walls by mastic or mortar, and it became particularly popular for resurfacing old ground-level commercial spaces for chain restaurants, candy stores, and other businesses for which it was desirable to present an up-to-date and hygienic appearance. Glass was enthusiastically accepted as a wall finish beyond its association with the admission of light.

The rush to erect office and commercial buildings after World War II and mounting costs of labor caused the virtual abandonment of masonry facings for such structures in the United States. The government's investment in factories to meet its wartime demand for aluminum provided a postwar source of extrusions that simplified the construction of curtain walls. Metal panels were often incorporated in these surfacing systems, but through the years glass in its various forms became the most accepted material. Air conditioning systems permitted the construction of sealed buildings in which walls no longer served a ventilating function. Given the economy of the glass-filled curtain wall, glass manufacturers assumed the challenge of altering their products in response to the problems that were inherent in such a wall. Glare in the interior was reduced with tinted glass; heat gain was lowered with heat-absorbing glass; and heat loss was lessened with double-glazing. With the introduction in 1966 of reflective glass, basically a one-way mirror said to transmit only about 10 percent of the solar energy striking a wall, buildings were no longer sculptured masses but became instead illusory forms with thin-lined grids marking off extensions of the sky.

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6

Cements

1756 John Smeaton experiments to determine hydraulic cement for the Eddystone Lighthouse

1796 Roman cement patented by James Parker

1820 Natural cement discovered in construction of the Erie Canal; patented (U.S.) by Canvass White

1824 Portland cement patented (Britain) by Joseph Aspdin

1858 Systematic testing of Portland cements for use in construction of the London drainage system

1870s German scientists improve the chemical analysis and processing of cements

1871 David O. Saylor obtains patent (U.S.) for production of Portland cement

1890s Introduction of cement made from blast furnace slag

6.1 The rebuilding of the Eddystone Lighthouse in 1756 was the impetus for John Smeaton's investigation of hydraulic cements. Because waves and fire had destroyed three previous lighthouses and the rock was awash at high tide, the use of the best hydraulic cement was essential, even with dovetail connections between the stones. Smeaton's structure lasted more than a century. (Eighteenth-century engraving, reproduced from R. W. Lesley, *History of the Portland Cement Industry*, 1924.)

It was the Romans who made the transition from lime mortar to cement mortar. Of these mortars Vitruvius wrote:

> Limestone when taken out of the kiln . . . is found to have lost about a third of its weight owing to the boiling out of the water. Therefore, its pores being thus opened and its texture rendered loose, it readily mixes with sand, and hence the two materials cohere as they dry, unite with the rubble, and make a solid structure. . . . There is also a kind of powder which from natural causes produces astonishing results. It is found in the neighborhood of Baiae and in the country belonging to the towns round about Mt. Vesuvius. This substance, when mixed with lime and rubble, not only lends strength to buildings of other kinds, but even when piers of it are constructed in the sea, they set hard under water.[1]

Lime mortar became strong through the chemical action resulting from its contact with air; but with the addition of pozzolana—the natural compound of silica alumina and iron oxide to which Vitruvius referred—a hardening reaction was achieved independent of air and deep within large masses of mortar.

For medieval buildings, simple lime mortar appears to have been customary. There is evidence that in the Rhine valley, tarras, a volcanic stone, was added to the mixture. A powder of ground brick or tile, which Vitruvius had recommended as a substitute for pozzolana, was also employed to strengthen mortar. From contemporary records and from ruins it is evident that medieval walls, like Roman walls, were made with a filling of mortar and rough stone. The Romans used brick and most medieval masons used stone to form the two faces of a wall, and between these surfaces mortar and scraps of masonry were placed. In both periods it does not appear that the stones and mortar were mixed together before being put in the wall.

Through their studies of Vitruvius's writings and the remains of Roman structures, later architects had constant reminders of the Roman development of a strong hydraulic cement (one that would set under water). When Sir Christopher Wren was building St. Mary-le-Bow after the Great Fire of London, "he sank about 18 feet deep through made ground, and then fancied he had reached the natural soil and hard gravel; but, upon examination, it appeared to be a Roman causeway of *rough stone*, close and well rammed, with Roman brick and [rubble] at the bottom for a foundation and all *firmly cemented*."[2]

* * *

Fourteen miles southwest of Plymouth harbor, long one of England's busiest ports, three ridges of rock called Eddystone lie near the surface of the water. The water around them is rough, even when the sea is calm. Shortly after the Eddystone Light burned on a December night in 1755, John Smeaton was chosen to direct the rebuilding of the lighthouse. Only 31 years old, Smeaton had two years before been made a Fellow of the Royal Society, and he had entered the field of engineering after several years as a maker of marine and astronomical instruments.

At high tide the rock on which Eddystone Light was to be rebuilt was covered by the sea, and the choice of mortar was critical under those conditions of construction (fig. 6.1). Smeaton began a series of experiments to determine the cement that