Mechanization of glass manufacture had just begun in 1898 but was accelerating. Notable advances were soon to be made in all branches of the industry, many of them in the United States, and have continued to the present day. M. J. Owens occupies a unique position as the inventor of the first successful fully automatic container machine in 1903; he was also involved in several other important developments. However, within 20 years, machines fed with gobs supplied by the Peller forehearth and gob feeder, also American inventions, became successful competitors. From about 1930 to 1960, a wide variety of machines was used to make containers, but these have been superseded nearly everywhere by the individual section machine, another American invention. The Lubbers process for sheet glass cylinders was an early success in 1903. About 12 years later the direct drawing of flat sheet was developed almost simultaneously by Fourcault in Belgium and Colburn in the United States. The Pittsburgh process followed a few years later. Ford was the first to succeed in making continuously cast plate, but Pilkington in the United Kingdom soon exploited that process to make much wider cast plate. At that time Pilkington also developed the simultaneous grinding of both faces of the continuous ribbon. The invention and development of float glass by Pilkington in the 1950s has made all other flat glass processes obsolete for most purposes. Owens–Corning has played a major role in the glass-fiber industry since its beginnings in the 1930s. The most important advance in manufacture of optical glass was the small continuous tank with vigorous stirring developed by Corning Glass Works. Corning also made other notable advances, such as the ribbon machine for lamp bulbs and the lamination process used for Corelle ware.

I. Introduction

The techniques of manufacturing glass products changed very little between the invention of glass blowing around 50 AD and the last few years of the 19th century. However, developments then became rapid, and many were the work of North American inventors and engineers. The centennial of The American Ceramic Society is thus a natural occasion on which to review some of those innovations. Enormous changes have occurred in methods, scale of production, range of products, and quality of glassware during the past century. By 1890, the Siemens regenerative furnace was already able to provide the continuous supply of molten glass needed for mechanized production.

The past century has been a turbulent one. The United States was expanding vigorously when The American Ceramic Society was founded, and there was much political unrest; employers and unions were often in conflict, sometimes physically. European culture was also in turmoil that led to World War I, to be followed only 20 years later by World War II. Rapid political and economic changes have continued ever since; all of these have inevitably affected progress in glassmaking. Many historians have written about these times; a particularly vivid account of the 25 years ending with the outbreak of World War I is by Tuchman.1

J. J. Thomson discovered the electron in 1897; the first commercially successful American automobile, the Oldsmobile, was put on the market in 1901; Planck’s theory of black-body radiation was published in 1910. Coast-to-coast telephone calls became possible in 1914; the first primitive television broadcasting system began transmitting in England in 1929. The atomic nucleus was split in 1945; Crick and Watson unravelled the structure of DNA in 1953; the transistor was invented in 1957.

Davis2 discussed the history of the glass industry in the United States, from the earliest times up to 1929, but his main interest was economics rather than technology. Scoville3 also described the early growth of the American glass industry and examined in detail the development of glassmaking companies in Toledo, OH, between 1880 and 1920, again as an economic historian.
II. Pressing

Pressing requires only suitable molds and muscle power with simple mechanisms; therefore, it has been exploited from very early times but can be used only for a limited range of shapes. Simple side-lever presses giving a considerable mechanical advantage were widely used a century ago. In the early years of the 20th century, pressing was widely exploited to make dishes, plates, cups, saucers, etc., often of rather low quality. In those days, pressing was the only process available for making large vessels, such as 100–200 L electric (lead–acid) accumulator jars.

The two major advances in pressing were to operate the machine pneumatically and to put several molds on a rotating table; these much increased the rate of production and decreased the labor needed. Such presses often used a spring cage and toggle action. W. J. Miller was one of the pioneers in manufacturing presses; he introduced a “one-man” press. Frank O’Neill, whose first machine was a power-driven press capable of making 27 pressings a minute (Meigh6), was another pioneer. The quality and range of pressed domestic wares then improved rapidly; pressed kitchen and ovenware of Pyrex became familiar by 1940.

Although pressing can use relatively high pressures to ensure very accurate shaping, surface quality is poor unless the molds are of the highest quality and conditions at the glass–mold interface are very closely controlled. A common defect caused by poor control is a series of parallel or concentric waves called washboard. Much of the early output bore deliberately patterned surfaces, partly to obscure mold seams and defects, partly to imitate expensive cut glassware. Pitt7 reported in 1918 that American decorative pressed ware was of much higher quality than that being made in Britain. Some high-quality pressed ware, difficult to tell apart from cold worked, was being produced in the United States during the 1930s.

Much higher standards of surface finish were being demanded by the 1950s for large items, such as television tube faceplates, and for complex surfaces, such as vehicle headlight lenses. Quality has continued to improve as customer demands have also increased. More sophisticated standards of engineering and better control of temperatures, pressing velocities, and forces, as well as mold surface quality have allowed these demands to be met. Valstar8 described some of the technological problems of making large color television faceplates. Lenses of good quality can now be pressed, and flat sheets of glass are pressed to form complex three-dimensionally curved vehicle glazing components.

The Corning Hub machine, invented by Giffen,9 is unlike any other press. It looks rather like a miniature Ferris wheel and is used to press Corelle ware from a ribbon of glass passing below the wheel.

III. Centrifugal Casting

In the late 1940s, the existing technique of pressing the cones for television tubes proved unable to keep pace with demand. Giffen10 at Corning solved that problem by developing centrifugal casting, although many experts thought it impossible to use that method. By 1949 he had produced a machine that could make 800 cones/d, and, thereafter, he also modified the process to make the bodies for tubes with rectangular screens. Other manufacturers, including some making patterned decorative domestic and artistic wares, then began to use this technique.

IV. Container Manufacture

(I) First Attempts

The mechanization of bottle and jar manufacture required several things.

(i) To begin by making the mouth or “finish” of the container.

(ii) To use a suitable parison mold, thereby reducing to two the skilled glass blower’s numerous operations in forming the body.

(iii) To use pneumatic or electric power to drive the machine and to provide compressed air, perhaps vacuum as well.

(iv) To have an efficient mechanical method for supplying gobs of glass to the machine.

(v) To use metal molds.

Ashley in Yorkshire undertook the first trials that led to success. His original machine attempted to use only one inverted mold with a loosely fitting movable base plate that could force the glass down into the neck ring and then serve to form the base of the bottle, using compressed air for blowing (Fig. 1). Ashley adopted this idea by Arnall, who had conceived it about 20 years earlier, and the two of them obtained patents in 1886.11,12

The first machine was too crude to work well, but Ashley saw that it could be refined. His next single-unit machine (Fig. 2) had all the essential elements of neck ring, parison mold, and blow mold. The inverted parison mold was filled through its base; then the parison turned upright before the final blowing. Ashley’s second patent included the use of suction around the outside of the parison for “blowing” it in the final mold as an alternative to blowing in the normal way; he also considered using materials that evolved gas when heated rather than an external air compressor. With two of those machines, one gatherer could make 1560 bottles in a 10.5 h working day.

In 1889, Ashley13 obtained further patents, the last of which was for a rotary machine with several (four) parison molds that used a pneumatically operated piston to open and close the parison molds as well as compressed air for blowing. A Leeds newspaper report described in awe-struck terms the manufacture of bottles on Ashley machines at Castleford, Yorkshire, in 1887. Compressed air is said to have first been used in a glass house at Baccarat in France and was sufficiently novel in 1883 to be reported to the Academy of Science in Paris (Appert14).

At one time Ashley had 10 of these machines in operation and two workers could make 180 dozen bottles/d on one ma-

Fig. 1. Ashley’s first method for blowing bottles. Glass is loaded into the inverted mold and pressed down using the movable base plate. Base plate is raised to the end of the mold and the bottle blown. Hinged mold is then opened to remove the bottle. (After British Patent No. 8677, 1886.)
machine (English\textsuperscript{15}). However, various problems, including hostility of the trade unions, led to failure of the firm some years later. These machines had the major disadvantage of needing a skilled worker to gather the glass and fill the parison mold, which limited the rate of production. This shortcoming held back the development of the rotary blow–blow or press-and-blow machine for more than 20 years.

Horne, who had built machines for Ashley, patented his own improvements and, by 1917, had sold more than 200 of his machines in Britain (Meigh\textsuperscript{6}).

A coherent history of the development of container machines becomes difficult from this point, because so many different glassmaking companies and numerous talented engineers devoted their skills and ideas to the problems of mechanizing production. Several different approaches were developed, and there are many tangled skeins in the history of container manufacture. Given the small size of the glass industry compared with the whole field of mechanical engineering, it is pleasantly surprising to see how many outstanding talents have served glass manufacture, but their achievements cannot all be included in a brief review. Fortunately there have been a few extended reviews, some chiefly about British practice (which has tended to follow that of the United States), such as Meigh\textsuperscript{16} and Clark,\textsuperscript{17} who reviewed his 50 years with his family firm, Beatson Clark of Rotherham, Yorkshire, which had been founded in 1751. During his career, Clark saw changes from semiautomatic machines with hand gathering to fully automatic production on individual-section (IS) machines. Giegerich and Trier\textsuperscript{18} produced a notable book describing all types of glass-working machines in use 30 years ago.

(2) Press-and-Blow Forming

Pressing the parison then blowing the body of the ware, with the finish still held in the neck ring, relaxes some of the restrictions on shape imposed by one-stage pressing. J. S. and T. B. Atterbury\textsuperscript{19} of Pittsburgh, PA, patented this method in 1873 for making molasses pitchers with a spout and handle. The same press-and-blow method was patented by Arbogast\textsuperscript{20} in 1882 for making bottles (Fig. 3), but it was not used commercially until 1893, when it was used by the Enterprise Glass Company for mass production of Vaseline jars.\textsuperscript{21} At that time, the glass still had to be gathered by hand. The process was soon being used for a considerable range of wide-mouth ware, including Mason jars. However, no machines for narrow-neck bottles were made in the United States until 1908, when copies of English machines were introduced (Meigh\textsuperscript{6}); some of these were called “Johnny Bull” machines.

Many semiautomatic press-and-blow machines were available about 1900 and 1940. In the early days, these usually required a gatherer, one worker at the parison table, and another at the blow mold table, sometimes with a worker to transfer the parisons from one to the other. It soon became possible for the gatherer to control the whole process by operating a pedal as soon as the mold had been filled. W. J. Miller\textsuperscript{22} of Swissvale, PA, was an early manufacturer of such “one-man” two-table press-and-blow machines. Rather primitive feeders began to replace the gatherer around 1910, and gob feeders improved rapidly from about 1918. Semiautomatic machines were all eventually superseded by automatic ones, generally similar to two-table blow–blow machines.

Edward Miller,\textsuperscript{23} of Columbus, OH, was a pioneer in manufacturing press-and-blow machines on a large scale; his JP and PB machines were very widely used. He sold his business to the Lynch Corporation in 1933.

(3) The Suction Process

Michael J. Owens\textsuperscript{24} (1859–1923) invented the first successful automatic machine for narrow-neck containers. Owens, the son of Irish immigrants, entered the glass industry in Wheeling, WV, as a boy aged 10 years and was already a blower at the age of 15. Over the next 10 or so years, he managed to acquire some education and to display undoubted ability.

In 1888, Edward D. Libbey, the owner of a Massachusetts glass company, was beset by strikes. The glassmakers’ unions were very powerful at that time in both the United States and Britain: in 1919, the British bottle-making industry still had 13 unions. Libbey therefore closed that factory and moved his operations to Toledo, OH, where natural gas and good sand were available. Owens there became one of a team of blowers making lamp chimneys. In 1892, Owens obtained his first patent\textsuperscript{25} for a mechanical device to replace the worker who

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Fig. 2. Ashley’s early machine. Inverted parison mold (A) and neck ring (B) are fitted to hand-held tongs. After turning the parison upright, the blow mold (C) is raised by a treadle (D) and the bottle blown.

Fig. 3. Illustrations from his patent of Arbogast’s press and blow process for containers.
crouched at the glassblower’s feet to open and close the mold. Within two years, Owens had become superintendent of the factory and two of his next four patents were concerned with improving the glassblower’s tasks.26

Owens later stated that the basic idea for a bottle-making machine occurred to him in 1898, but it took five years of extensive experimentation, generously supported by Libbey, to produce a useful machine. Owens proved himself a towering but rather abrasive genius of practical engineering insight and skill in glassmaking who could devise an effective solution to nearly every problem that arose, thus justifying the unstinting support of Libbey. Together they brought revolutionary change to several branches of the glass industry, most of all to the manufacture of containers.

Owens recognized that gathering the correct quantity of glass was the first important problem, and he solved it in a novel way, by using suction to fill a gathering mold (Fig. 4). By 1903, he had invented the rotating pot (a shallow dish fed from a tank27). This allowed each gather to be made from fresh glass not chilled by the previous gather (Fig. 5), but it increased the fuel consumption of the furnace. In 1903, he also built his fourth machine with six arms. Trials with this machine at the Toledo Glass Company proved that automatic production of bottles was possible, and the Owens Bottle Machine Company was established that year. Further improvements followed; the next experimental machine still had six arms but had become continuously rotating. The whole rotating mass of several tons was, however, still lowered and raised each time that glass had to be gathered. This became the type-A machine, several variants of which were developed during the next few years. The dipping-head machine (type AN) was introduced in 1912. Each head now dipped by itself for gathering and was a self-contained bottle-making unit. The final stage of forming naturally required compressed air for blowing and for mold cooling. Many of the operations were controlled by cams mounted on the central pillar of the machine. This gave very precise movements but permitted only minor adjustments of many of the individual operations. The Owens machines were outstandingly beautiful pieces of engineering; some data about the various models are given in Table I. The OS six-arm machine was designed and made by Schwartzkopff, the Owens Company’s European agents.

The 15-arm machines (AQ and AV), first licensed in 1914, could produce as many bottles as 50 blowers working by hand. The 10-arm CA and CB machines, fitted with 20 sets of molds, rotated at ~4 rpm and could produce 80 bottles/min. Owens also introduced multiple-cavity molds (up to four per mold), a refinement much easier to fit on a suction-fed machine than one supplied by a gob feeder. The AT carboy machine was huge and weighed more than 100 tons. It could make 5 gallon bottles at five or six per minute (Meigh6). The number of Owens machines working in the United States increased from 8 in 1906, to 103 in 1911, and to 187 in 1916 (Weeden28). The first Owens machine in Britain was installed at Alloa, in Scotland, in 1919, and led to a bitter dispute with the blowers and furnace workers, but that was not typical of the response of the workers to machines.
The Redfern machine, designed to make whisky bottles, was an initially successful British competitor for the Owens machine; it was first installed in 1920 at the works of John Lumb in Castleford, Yorkshire. The two machines appeared similar, gathering and working the glass in similar ways, but they differed greatly in many details of the engineering. For example, the main rotary drive of the Redfern ran in an oil-filled channel, complete individual parison or blow mold units could be changed very quickly, and all main-drive links were spring loaded to minimize risk of damage. According to Dralle and Keppeler, an Owens machine needed to be stood down for two or three hours at least once every two weeks for cleaning, adjustment, and lubrication, but a Redfern machine could run for months without stopping for those purposes. The 15-arm Redfern machine was 5.1 m in diameter and weighed ~60 tonnes; there were also six- and ten-arm versions.

An Owens machine used ~6 hp to drive the machine itself, only twice as much as the rotating pot, but vacuum, compressed air for blowing, and cooling air added another 47 hp (Dralle and Keppeler). U.S. government statistics for glass-container manufacture in 1927 showed that machines increased productivity by factors of from 6 to 41 over hand methods and that labor costs fell by more than 90% for many products.

Of the Owens–Illinois Company, one of the most famous in container manufacture, was formed in 1929. Despite their brilliant engineering, Owens machines were not popular with all glassmakers. They were large (the CA was more than 5 m in diameter) and costly: A complete Owens unit cost $80,000 but could work out 70 tons of glass and make more than 100,000 containers/d. Owens machines were best suited to making long runs of one type of container; a very heavy investment in molds was required when several types of container were to be made. Moorshed reported that the CA machine needed a larger rotating pot (~4 m in diameter) than the other models and, thus, an even greater amount of fuel.

The quality of the containers was outstandingly good for those days, but they had one technical flaw that proved impossible to cure: the “cut-off scar.” This was a fold in the bottom of the base where a chilled tail had been formed as the knife cut through the base when the glass had chilling by the previous gather. It could make containers with internal screw finishes having a wide range of capacities and needed only 2 hp to run it. Weekly production was up to 1100 gross of 3 or 6 fl oz (90 or 180 mL) bottles in double-cavity molds and 200 gross of 80 fl oz (2.4 L) Winchester (Creaser, Creaser, and Hodkin). Monish machines were still being used in the 1950s (Clark).

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There were commercial disadvantages over the way that licenses were granted, as well as the cost. Initially, strict conditions over the types of ware that could be made were imposed on licensees, who, of course, also often complained about the royalties they had to pay. Biram recorded details of the legal contracts under which Owens machines were used in Europe from 1907 to 1962. Opportunities therefore remained for other machines that were smaller, less expensive, and more flexible in operation. The major competitors were blow–blow or press-and-blow machines fed by gob feeders. Such machines were eventually produced, but their success depended on first inventing an effective gob feeder to supply them.

Other inventors of machines using suction gathering often followed different ideas or ones discarded by Owens. They usually wanted to produce smaller, simpler machines not needing a special gathering pot that was almost as big as the machine itself and used excessive fuel.

One of the successful European manufacturers was Emile Roirant (1882–1955), in France. Roirant was an engineer of outstanding talent, one of whose favorite sayings was, “Always remember that any idiot can make a complicated machine.” The Roirant B machine, introduced in 1922, had one pair of molds, and many of its operations were controlled by a large cam rotating about a horizontal axis (Fig. 6). The machine could be wheeled up to a furnace to gather from a normal working hole. The Roirant A6, which followed in 1928, was a six-station, intermittently rotating machine using cams to control the opening and closing of the molds. The BB2 machine, patented in 1935, could make good-quality containers of capacity from 10 to 60 L at a rate better than one per minute. Roirant’s last machine was the single-table, continuously rotating, seven-arm feeder-fed R7 introduced in 1950.

The other notably successful machine using suction gathering was the paste-mold Westlake machine. It is discussed in the section on lamp bulbs and continues in use for thin-walled drinking glasses and stemware. The Monish was another quite widely used, small, intermittently rotating, three-mold suction machine, made by Moncrieff in Scotland. It gathered the glass from a small horseshoe-shaped channel and used a paddle in the forehearth to avoid gathering glass chilled by the previous gather. It could make containers with internal screw finishes having a wide range of capacities and needed only 2 hp to run it. Weekly production was up to 1100 gross of 3 or 6 fl oz (90 or 180 mL) bottles in double-cavity molds and 200 gross of 80 fl oz (2.4 L) Winchester (Creaser, Creaser, and Hodkin). Monish machines were still being used in the 1950s (Clark).

(4) Gravity Feeder-Fed Machines

Most machine designers wanted to develop simpler, feeder-fed, two-table machines, with parison molds on one table and blow molds on the other. Many designs made blown parisons, but some were press-and-blow machines. At first, these machines generally moved intermittently, and operations were done only while stationary. Many machines had six molds on each table, so that a maximum of six operations could be performed in forming the parison or in blowing the bottle. A two-table machine need not have equal numbers of parison and blow molds, but that arrangement was easier to engineer (Fig. 7). These machines initially often needed a “boy” to transfer the parisons to the second table as well as to remove the finished ware. Such semiautomatic machines (sometimes with only three or four stations) could still be seen in many European factories during the 1950s, mostly for short production runs.

Within a few years, it became possible to eliminate the “boy;” the first machines to do so, introduced by Lynch and Miller in 1917, were therefore named “No-Boy.” By mounting other components besides the molds on the tables, it soon became possible to execute operations while in motion. This accelerated the whole process and opened the way for some machines to become continuously rotating. That saved time, a great deal of mechanical energy, and much decreased wear and tear.
The earliest gravity feeder to be used, in 1903, was invented in New York by Homer Brooke, who had been born in Yorkshire. His feeder used a steady stream of relatively fluid glass. When the mold was full, this stream was sheared and gathered by a cup that was tipped up to hold the glass until the next mold was in place; the cup then dumped its contents into that mold (Fig. 9). Four sets of cups and shears were mounted on a rotating table. The main defect was poor thermal homogeneity of the glass in the parison mold caused by chilling of the rather thin stream of glass as it collected in the cup. However, it was adopted by several companies, including Hazel–Atlas and Ball Brothers, for cheap wares. Hazel–Atlas obtained a patent for such a device, but with the shears above the cup, as late as 1925 (Stenhouse).

The Hartford–Fairmont Company had been established in 1912 to build new and improved glassmaking machinery to compete with Owens. Finding another way of supplying good-quality glass to forming machines was one of its important objectives, and Karl Peiler, a 1904 graduate from Massachusetts Institute of Technology, was already working on this task. Peiler remained with the company for 42 years.

Peiler decided to work with glass at about the viscosity used for hand gathering (more viscous than for a suction machine) and also to attempt to mechanize the manual operation of a gathering iron, as shown in Fig. 10. The gathering iron rotated continuously while inside the furnace but stopped when retracted so that gravity would form a pendant mass that was cut with shears; unfortunately, that proved difficult to control accurately. The second attempt was to produce the gobs intermittently using a paddle having both vertical and horizontal movements that made the glass surge over the rim of a refractory bowl. Peiler also conceived another way of achieving this result using two adjacent refractory bodies dipping into the glass but moving only vertically; by reciprocating more or less alternately, they could achieve the same result. The hanging mass was again severed by shears at the right moment to allow the gob to fall into a chute that led it into the mold. This worked rather better, and some Hartford paddle feeders were used in the industry, from 1915. Those feeders allowed both O’Neill and Miller to make useful, fully automatic machines from 1916.

However, those feeders also proved unable to give the control desired. Peiler therefore added a bowl containing a reciprocating needle into which the glass dropped, to give the required finer control and some shaping of the gob (Fig. 11). This paddle–needle feeder was first used in 1915. By 1918, 120 of these feeders were already in use (Meigh). However, it turned out that they only gave good control of gob weight and shape at high speeds of operation. They were therefore often used to supply two or three machines using a swinging distributor, a precursor of that later essential for the IS machine.

Peiler then turned to another way of controlling gob formation. That method used the reciprocating vertical motion of a larger plunger above a concentric orifice through which the viscous glass flowed. A concentric tube around the plunger restricted the effect of the plunger to the glass in and immediately above the orifice. Peiler produced the first model of what is now the standard type of feeder in 1922 (Fig. 12). This feeder uses cams to give positive and reproducible motion of the various elements; rotation of the tube improves thermal homogeneity in the nose of the bowl. The company was renamed Hartford Empire in 1922, after taking over the Empire Machinery Company from Corning Glass Works, and again in 1951, when it became Emhart.

Dowse and Meigh reviewed in detail the state of feeder development in 1921. Another generously illustrated review, taking the story rather further, appeared in 1932 (Swain), but that strangely does not mention the paddle–needle feeder. Peiler’s feeder has since undergone many improvements, but the basic design and operation remain remarkably similar to the original model; the essential elements remain the orifice, the reciprocating plunger, the rotating tube, and the shears. A no-
table modification enabled it to deliver double, then later triple or even quadruple gobs to the forming machines. That allowed simultaneous production of more than one container in one mold body having more than one cavity; the process had been an early and rather simpler development with suction machines.

Successful operation of the feeder required a constant supply of glass of a particular uniform viscosity so that the glass had to be cooled and made thermally homogeneous between the working end of the furnace and the feeder bowl. The construction of furnaces and machines also made it necessary to distribute the glass to machines some distance apart. Much longer forehearth channels than originally used thus became desirable, and much work was done to develop forehearths that fulfilled the need for constancy of temperature and thermal homogeneity despite variations within the furnace. Hartford took a leading role in that task. Hartford feeders were brought to Britain in 1917 by W. A. Bailey, who set up the British Hartford–Fairmont Syndicate, which, in 1918, began to operate a paddle-needle feeder with a Hartford milk bottle machine at Key Glass Works, New Cross.

The basic features of the modern forehearth were introduced in 1922. Forehearth design and control have improved hand in hand with the gob feeder. Relatively early patents included sealing the combustion space of the forehearth from the working end of the furnace and the feeder bowl. The construction of furnaces and machines also made it necessary to distribute the glass to machines some distance apart. Much longer forehearth channels than originally used thus became desirable, and much work was done to develop forehearths that fulfilled the need for constancy of temperature and thermal homogeneity despite variations within the furnace. Hartford took a leading role in that task. Hartford feeders were brought to Britain in 1917 by W. A. Bailey, who set up the British Hartford–Fairmont Syndicate, which, in 1918, began to operate a paddle-needle feeder with a Hartford milk bottle machine at Key Glass Works, New Cross.

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automated the operations of hand gathering, as Peiler first attempted to do, or returned to gathering by suction. These are especially useful for very large gobs (Lindner), such as are needed for large television screens.

(6) The Individual Section Machine

The IS machine has now displaced almost all other container machines. It was invented in 1924 by Henry Ingle of the Hartford Empire Company, but the patent was not granted until 1932. Ingle himself named his machine “Individual Section.” However, Meigh reported that the abbreviation “IS” was already widely used when he saw the first four-section machines in 1927. It was assumed to have been adopted to recognize both the inventor, Henry Ingle, and the President of the Company, Charles Goodwin Smith. Smith supported Peiler and Ingle in the way that Libbey had supported Owens. Many of the developments of the IS machine up to 1960 were guided by George Rowe, who joined the company in 1924.

The IS machine introduced several novel features; a 1923 patent granted to Ingle indicates how big a step forward the IS machine represented. A well-illustrated description of it was published in 1928. The most revolutionary features were that each section could operate independently and that the arm carrying the neck ring moved in a vertical half circle to transfer the parison to the blow mold. Both parison and blow molds remained stationary; the only essential horizontal motions were the opening and closing of the molds and neck rings, and the removal of the finished ware (Fig. 13). The machine was built from as many sections as desired, mounted side by side, and provided with one long horizontal main drive shaft. In the 1950s, a five-section machine was considered large, but as many as 16 sections are now in use. Although all sections receive gobs of the same weight, it is possible to make containers of somewhat different designs on the various sections.

The IS machine is compact, each section is only ~0.7 m wide, but tall. Another very attractive original feature was the use of an easily accessible large-diameter timing drum to carry the on–off controls for all the essential pneumatically controlled operations (at least 19). This gave accurate control and very wide flexibility in settings, something not possible with many of the operations on the Owens machine. Electronic control was introduced in 1974.

The IS machine did not achieve its present dominance for many years. It was expensive and, like the Owens, for some years, could only be licensed. Although much more flexible than the Owens machine, it too was generally perceived as best for very long production runs. Double-gob operation (making a pair of containers simultaneously in one mold body) was introduced in 1939 and triple gob in 1967. The technical superiority of the IS machine has been supported by a first-class commercial and engineering organization that expanded to cover almost the whole world.

Ingle also recognized the need for a good alternative to heavy iron boxes or solid iron slats for carrying the ware in the lehr. He realized that heating and cooling large amounts of iron consumed a lot of energy and limited the rates of heating and cooling that could be achieved. Two of his patents are for the use of lightweight metal mesh for the lehr belt. This belt had alternate sections woven right-handed and left-handed to avoid creep of the belt to one side. The use of the mesh belt also permitted much better gas circulation in the lehr and, therefore, better temperature control.

As machine performance improved, the rate at which heat could be extracted from the metal molds became a limiting aspect of machine operation. The basic design of the IS machine allowed better mold cooling than other machines because the molds remain in the same place. Giegerich published an interesting study that compared the relative efficiencies of several types of bottle machine and showed that the IS machine performed best from most points of view. The Vertiflow system of making air flow through vertical passages drilled in the mold bodies was a major advance in mold cooling. This gave better control of temperature distributions in the molds,
decreased the consumption of compressed air, and reduced noise levels.

The 62 process for making pressed parisons for wide-mouthed ware, such as jam jars, was introduced in 1940. Pressing of the parison makes it much easier to ensure complete filling of the neck ring and accurate formation of the finish. By also guaranteeing the internal shape of the parison, it improves control of wall thickness in the finished article. The most important advance of recent years has been the widespread use of press-and-blow for narrow-mouth containers. This uses machines and materials very close to the limits of what is possible. The narrow-neck press-and-blow process is now considered essential for further progress toward thinner walls and lighter ware. It is accepted that ensuring a minimum wall thickness of 0.8 mm requires a designed wall thickness of about 2.0 mm for blow–blow but only 1.3 mm for the press-and-blow process.

During the past 40 years, much research has been done and various technically advanced and promising machines have been developed by other engineers. Owens–Illinois, for example, spent many years investigating the crucial factors in container production that could help to improve performance and might lead to better machines. These potential competitors included the Lynch 44,61 which had individual sections, like the IS machine, but the basic sequence of operations used three stations (parison forming, blowing the container, and take out) with three neck rings rotating about a vertical axis.

Another machine of great promise in the 1970s was the Heye 6-12.62 This was a two-table narrow-neck press-and-blow machine with an unusual layout. The tables were some distance apart and rotated about vertical axes; the blow mold table was bigger and carried more molds than the parison table. A continuous belt bearing multiple neck rings carried the parisons to the blow molds and the finished containers away to the discharge point. A machine having different numbers of parisons and blow molds recognizes that the two parts of the whole operation do not necessarily need the same times, and that this could improve efficiency.

However, no other new machine has to date proved able to compete with the IS machine. This has been partly due to the heavy investment in capital, spares, operating experience, and so on, that most manufacturers have already made in IS machines. Radical changes to the IS machine itself would face obstacles similar to those of other competitors, but it is difficult to believe that further major advances will not occur. A recent Emhart patent (Jones63) adapts the IS machine to transfer the parison to an intermediate station where the blow mold encloses the parison and the neck ring is released; after reheating, the blow mold is moved linearly to the final blowing position. Edgington64 has written a detailed history of Emhart.

V. Flat Glass

(1) Sheet Glass

In the 1890s, two processes existed that had long been used to make window glass. Broad, or cylinder, glass was made by blowing uniform cylinders as large as possible, cutting off the ends, then splitting them longitudinally. These were reheated in a special furnace and flattened, using a special rake to open them out. Cylinder glass nearly always had some surface damage, with waves or ripples on both faces, caused by the action of the rake and contact with the substrate. Cylinder glass was unsuitable for mirrors or for windows intended for undistorted vision rather than merely admission of daylight. However, the introduction of some simple mechanical aids during the second half of the 19th century had led to improvements, as much in the size of the cylinders and productivity, as in the quality of the glass. These aids supported the horizontal blowpipe while reheating at the glory hole and provided a pivot for swinging the cylinder to elongate it after reheating.

Crown glass was made using centrifugal force to spin a carefully formed shallow bowl of glass into a circular disk. Both faces of the disk were therefore fire polished, but the disk was always slightly saucer shaped and had a central thickened region, the bullion, where the punty had been attached. The natural fire-finished surface quality was much better than with cylinder glass, apart from the inevitable curvature; however, any inhomogeneities in the glass formed slight imperfections visible as arcs of circles on the surfaces. The largest panes that could be cut from crowns were smaller than could be produced from cylinders. Nineteenth century English glassmakers became especially skilled in the crown process. The natural curvature of the crown was less than that of mirrors commonly made by cutting pieces out of large blown spheres. However, crown glass had become obsolete by 1890, except for special purposes, including microscope cover slips and colored sheet for stained-glass windows.

The first important step toward mechanization was the Lubbers65 process, on which development work began in 1894. It was patented in 1902 and brought into commercial operation by the American Window Glass Company in 1903. This mechanized the vertical drawing of cylinders. Initially, glass was cast into a special preheated bowl, and a vertical blowpipe carrying a circular lidlike bait lowered into the glass. As soon as the glass had adhered to it, the bait was raised. Compressed air was blown into the emerging cylinder; both the upward drawing velocity and the blowing air pressure were carefully controlled to produce a cylinder of uniform diameter and wall thickness over most of its height (Fig. 14). Cylinders up to 13 m long and 1 m diameter were produced, and they needed 15–18 min to be formed (Turner66). However, the cylinders still had to be cut in shorter sections, then split and flattened, so

Fig. 14. Drawing a cylinder of glass by the Lubbers process. Glass is cast into a (A) reversible preheated bowl sitting on top of a (B) heated muffle. (C) Bait is dipped into the glass; when the glass has adhered, the blow-pipe unit is raised up the (D) vertical track.
that optical properties generally were little, if any, better than with handmade mouth-blown glass.

The Lubbers process was an immediate commercial success. In the years from about 1895 to 1903, the United States annually imported more than 20,000 tonnes of sheet glass from Belgium; in 1904, this abruptly fell to 12,700 tonnes, and imports never again reached former levels. By 1923 more than 60% of the window glass produced in the United States was made by the Lubbers process.

Numerous inventors attempted to draw flat sheets directly but had to attempt to overcome two natural laws: first, that any jet of liquid is inherently unstable and, second, that it tends toward a circular cross section. A British patent by Clark in 1857 recognized that forming a flat sheet by upward drawing required some way of stabilizing the width of the sheet (he claimed the use of immersed metal hooks at each side) and rapid chilling of its edges. A French patent of 1871 by Vallin, a cylinder-sheet manufacturer, had very similar ideas (Bore19). Success eventually attended the efforts of two inventors, one in Belgium and one in the United States.

Emile Fourcault (1862–1919) of the Dampremy glass works in Belgium obtained French and U.S. patents for his process in 1902 and later obtained several British patents. He had to overcome many difficulties before managing to make salable glass in 1916. One of the major customers in war-torn Belgium was the German occupying power; Fourcault then suffered grievously for being considered to have traded with the enemy, and this may have contributed to his early death.

Fourcault’s major invention was to stabilize the foot of the sheet using a “dBiteuse,” a long clay boat floating in the glass and having a carefully shaped long slot in its base. When the dBiteuse was slightly depressed, glass flowed up through the slot. If the glass was immediately gripped, pulled up, and cooled rapidly, it formed a vertical sheet (Fig. 15). The emerging sheet passed between water-cooled iron boxes, placed just above the dBiteuse, quickly making it sufficiently viscous to avoid the development of catastrophic instability. The method described in the first patent drew the sheets up a vertical tower by a simple apparatus remarkably similar to a guillotine working in reverse; the tower also served as the lehr. The use of several (typically 12–14) pairs of asbestos-covered rollers that pressed very gently on both faces of the sheet, to make the process continuous, came later. Fourcault’s first patent included the options of drawing cylinders or bending a continuously drawn sheet over a roll and leading it away horizontally into the lehr.

The stream of glass flowing through it eventually corroded the dBiteuse. Long threads of corrosion products then contaminated the surfaces of the sheet, causing obvious optical distortion, and the dBiteuse had to be replaced. The glass in the drawing chamber had to be held so near the liquidus that devitrification inevitably developed, and production also regularly had to be interrupted (approximately every 10 days) because of this.

Irving W. Colburn (1861–1917), an inventor from Fitchburg, MA, was inspired by seeing a paper mill. His father had worked for Owens (Owens and H. J. Colburn had a joint patent in 1897). He began to experiment with an upward drawing process at about the same time as Fourcault. Colburn’s successful process differed from Fourcault’s in two essential ways. First, the glass was taken directly from the free surface of the melt, and the edges of the sheet were stabilized by driving the glass upward using rotating bodies. Second, once the sheet had been formed, it was bent over a polished metal roll and carried away horizontally into a lehr, clearly more convenient than a vertical tower if the space was available (Fig. 16); however, this was not included in the first patent.

Colburn continued trials at his own expense until his funds were exhausted in 1912, and all his assets, including plans and patents, were put up for sale. Colburn then appealed directly to Owens and convinced him that the process could succeed. The Toledo Glass Company then took over the project, employing Colburn as a consultant, and the success of their initial trials led to formation of the Libbey–Owens Sheet Glass Company in 1916; unfortunately, Colburn, like Fourcault, did not live to see his process achieve commercial success (Clarke72).

Initially, Colburn used partially immersed spheres to attempt to pull and stabilize the sheet. To avoid infringement of the patents of either Fourcault or Libbey–Owens glass regularly to match that of good cylinder glass and render the Lubbers process obsolete. The Pittsburgh Plate Glass Company (PPG) process for vertical drawing of sheet formed the foot of the sheet in the same way as in Colburn’s process but drew the sheet up a vertical tower similar to Fourcault’s. This combination presumably avoided infringement of the patents of either. The PPG process, largely the work of Slingluff,78 was patented and came into operation in 1926 but, similar to the other processes, took several years to produce top-quality glass regularly.

In 1927, Gross provided data about the relative costs of making sheet glass by the different processes (Table II). The Lubbers process used extravagant amounts of fuel and the Libbey–Owens (Colburn) process needed the least labor. The Libbey–Owens–Ford Company was formed in 1930 by the merging of Libbey–Owens with the Edward Ford Glass Company of Rossford, OH; Edward Ford’s father was one of the founders of PPG (see below).

Having remained committed to the cylinder process, Pilkinson who had interests in Canada as well as Britain, initially failed to obtain licenses for either the Fourcault or Libbey–Owens process, after first backing an unsuccessful downward drawing process. Pilkinson was, however, able to take up the PPG process in 1931, when four machines making glass 94 in. (≈2.4 m) wide were installed. These performed so well that another four machines making glass 132 in. (≈3.4 m) wide, the widest in the world, were installed the next year. In 1933, the year that they abandoned the cylinder process, Pilkinson at last acquired rights to use the Fourcault process and, in 1934, was using it to make 80 in. (≈2.0 m) wide glass only 1.2 mm thick.

All three of these processes coexisted for several decades, each having somewhat different advantages and limitations. With all of them, devitrification in the drawing chamber peri-
odically forced a shut down. Rates of production varied; for example, the drawing speed of 4 mm sheet was ~0.50 m/min for the Fourcault process but 1.0 m/min for the Libbey–Owens, and 0.80 m/min for PPG (Goerk81). Annual production of a Libbey–Owens machine was ~1.3 × 10^6 ft^2, (1.2 × 10^6 m^2) four times that of a Fourcault machine. The Fourcault process, at least, continues to be used for thin sheet and for short runs of, for example, special colors. However, all have been replaced by float glass for most purposes.

Asahi,82,83 in the 1970s, patented a new sheet-drawing process that could be installed in an existing Fourcault installation. It was capable of making good-quality sheet 0.7–6 mm thick. Its features included two immersed parallel rotatable cylindrical bodies forming a slot through which the glass flowed up, with edge blocks at the ends of these bodies. These in effect formed a débituse of adjustable width. There were also rolls, similar to those of the Colburn process, to grip the edges of the sheet just above the surface of the melt.

Thin glass for microscope cover slips, liquid-crystal devices, and other applications in modern electronics is the one type of glass not easily made by the float process (described below). Numerous methods of drawing such glass have been proposed in the past 60 years. A Corning down-draw process for microscope cover glasses using a platinum drawing die was granted a patent in 1947 (Brown84). A very elegant later Corning down-draw process (Dockerty85) allows a steady stream of glass to flow over both sides of a special platinum channel to form a thin sheet as it falls away from the keel along the lower edge of the boat (Fig. 17). Both surfaces thus have a natural fire polish. That patent is unusual in that it is little more than a detailed mathematical analysis of the critical requirement of the apparatus, that is, how to vary the internal depth of the channel, of otherwise constant dimensions, to obtain the same thickness of the overflowing layer along the entire channel.

Some other processes rely on the Newtonian behavior of a preform to maintain its cross-sectional shape when extruded at a viscosity sufficiently high to make stresses due to surface tension effects much smaller than the other stresses involved (Humphrey,86 and Roeder and Egel-Hess87).

(2) Plate Glass

In the 1890s, plate glass with perfectly flat polished surfaces could only be made by the method invented in France around 1695. Plate glass was first made in the United States, in 1870,

<table>
<thead>
<tr>
<th>Process</th>
<th>Wages</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mouth blown</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Lubbers</td>
<td>38</td>
<td>146</td>
</tr>
<tr>
<td>Fourcault</td>
<td>25.3</td>
<td>60</td>
</tr>
<tr>
<td>Libbey–Owens</td>
<td>9.5</td>
<td>65</td>
</tr>
</tbody>
</table>

*After Gross.79*
by J. B. Ford\textsuperscript{88} (1811–1903), a riverboat captain, who was later one of the two founders of PPG, and lived for many years at Creighton, PA. In this classic procedure, the contents of a special large pot were cast onto a metal table and the glass rolled out by a heavy metal roller running on metal guides of appropriate thickness placed along each side (Fig. 18). The slab was then pushed into a lehr. After annealing, it was cut into smaller pieces for grinding and polishing. Although the basic process remained the same, the quantity of glass cast had increased during the 19th century, and the details of the apparatus improved, especially for grinding and polishing. However, the cast plate still had to be almost twice the intended final thickness if all low spots were to be eliminated during grinding. Grinding with sand and then polishing with rouge were very expensive in time, mechanical power, and labor. In 1924, Fick\textsuperscript{89} reported that a grinding table, 36 ft (~11 m) in diameter needed 500 hp to operate it, and a polishing table of the same size, 700 hp. These processes used 80\% of all the electrical energy consumed in a plate glass plant.

The first important advance was the second version of the Bicheroux process, introduced in Germany around 1920.\textsuperscript{90} That process made some important changes in the casting of glass from a pot of 0.85 m\textsuperscript{3} capacity. The glass was poured from the long side of an oval pot onto a casting tray that could be tilted; the glass flowed down this tray to run between two horizontal rollers of equal diameter. These rollers extruded the glass to the required thickness and delivered it on to a table moving forward below the casting unit at the appropriate rate (Fig. 19). One of the important improvements was to rotate the pot about the lower edge of its lip, rather than its center of gravity, during casting. Powerful cutting knives chopped the cast plate into several pieces as the table moved forward. This process increased the maximum size of plate that could be cast from 31.5 to 60 m\textsuperscript{2}. The Bicheroux process continued to be used for some purposes by Pilkington at St Helens, Lancashire, until 1958 (Pilkington\textsuperscript{91}).

By the end of World War I, the Ford Motor Company was experiencing difficulty in buying the large quantities of plate glass that they needed (Fig. 20); therefore, Henry Ford decided that the company should make its own. One of Ford’s senior engineers, C. W. Avery, was put in charge of this project although he knew nothing about glassmaking. After about two years of unsuccessful experimentation and expenditure of $1.5 million, Avery, in 1921, at last succeeded in solving all the problems of continuous casting (Fig. 21) but still did not have a furnace capable of providing glass of sufficient quality. At that stage, Pilkington heard about this work, and a visit was arranged to see the Ford plant. One of the Pilkington representatives, R. F. Taylor, was greatly impressed by what Avery had achieved and recognized its potential. Pilkington quickly decided to make their own trials to demonstrate that glass 6 ft (~1.8 m) wide, considerably wider than Ford needed for automobile windshields (40 in. (~1.0 m)), could be made by the Ford process. These trials were successful, but Ford was still not melting glass of good enough quality. In 1923, Ford’s original plant at Highland Park was producing only 7\% of the glass that they needed, but a new factory to have four furnaces

![Fig. 18. Late 19th century French plate-glass casting hall. There should be two workers at the far end of the roller, just as there are at the near end. (After Peligot\textsuperscript{171})](image1)

![Fig. 19. Improved Bicheroux process: (1) pot is brought to the horizontal tray; (2) pot is rotated about the lowest point of its lip to begin pouring onto the tray; (3) as pouring continues, the tray is raised and the glass extruded between the rolls and carried away on the casting table.](image2)
Glass ribbon is then carried away horizontally into the lehr. in. (102 cm) width before it passes under the upper 9 in. (23 cm) roll. diameter main roll, which rotates at glass 14 in. (36 cm) wide falls onto the top of the 48 in. (123 cm) patch was 7.5 h.

In 1922, Pilkington, having developed an improved continuous grinding machine that they offered to Ford, was able to negotiate a mutually satisfactory contract for exchange of experience. Pilkington staff were sent to Detroit to assist Ford with furnaces and grinding equipment while continuous casting was put into operation at Cowley Hill, St Helens. By 1924, Pilkington had made a ribbon 72 in. (~1.8 m) wide, but their continuous grinder could handle only 60 in. (~1.5 m) width; by 1927, the grinder had become capable of dealing with glass 100 in. (~2.5 m) wide (Barker94). Turner,95 in 1924, mentioned a few facts about the process. However, neither Ford nor Pilkington made any further public announcement about continuous casting until a report by Partridge96 appeared in 1929 and added a few more details. The casting rolls were both of cast iron. The larger roll, 48 in. (~1.2 m) in diameter, had a milling cutter mounted on its frame so that its surface could be dressed, when necessary, without having to remove the roller from the casting machine. The elapsed time between the glass emerging from the furnace and the polished plate being ready for dispatch was 7.5 h.

A lecture by Turner66 in 1930 was the occasion for public announcement of the history and then current state of continuous casting. In 1931, Libbey–Owens–Ford acquired some other plate glass plants and obtained a 7 year contract to supply General Motors Corporation with nearly all the glass that they would need.

Presumably because of widespread interest in rolled plate at that time, Glass Industry took the unusual course of publishing an English translation, by F. W. Preston,97 of the entire chapter on that subject written by E. Lutze98 for Dralle and Keppeler’s book. It appeared in 25 parts in Glass Industry from October 1930 to October 1932.

The Ford process allowed a controlled stream of glass 14 in. (~0.36 m) wide to flow from the furnace onto the upper surface of a large water-cooled roller, where it spread sidewards. After it passed under a 9 in. (~0.11 m) diameter upper roll, also water cooled, the ribbon of glass was carried into the long lehr (Fig. 21). At the end of the lehr, the glass was cut into 113 in. (~2.9 m) lengths for grinding then polishing on two lines, each about as long as the lehr. The first of these ground and then polished one side, the second doing the same with the other side. There were more than 40 grinding heads (Partridge reports 29 using sand and 14 using garnet) and 35 or 36 polishing heads (using rouge). The glass being ground and polished was carried on cars running on rails and clamped together after the slabs of glass had been set in plaster of Paris. The blanks for 0.25 in. (~6 mm) plate were cast 0.375 in. (~9 mm) thick and weighed 75 lb (~34 kg); after grinding and polishing the weight had decreased to 51 lb (~23 kg), a 32% loss. The Pilkington version of the Ford process made a considerably wider ribbon of glass and a range of thicknesses.

The next important advance was a twin grinder able simultaneously to grind both faces of the still continuous cast ribbon. Pilkington engineers had made sufficient progress with this by 1932 to begin to turn their attention to the problems of a twin polisher. The first production line with a twin grinder was commissioned at Doncaster, Yorkshire, in 1935. Its length from the doghouse to the end of the twin grinder was 1400 ft (427 m). The grinder itself occupied 300 m and consumed 1.5 MW of electric power. The glass originally moved through that twin grinder at 66 m/h, but, as improvements were made, this was later increased to 300 m/h.

The twin polisher was eventually developed but never exploited on a large scale. The dissipation of the heat generated when polishing both faces simultaneously was one important problem when there was no generous supply of coolant, as in grinding. For example, patents concerning the cleaning of the lower polishing heads were granted to Waldron and Griffin,99 Waldron,100 and Baillie in 1947.101
After 1930, some plate glass was produced from thick drawn sheet. This practice was at least a century old with thick cylinder glass: J. T. Chance had obtained a patent for such a process in 1838. This possibility having been foreseen and considered undesirable, Fourcault licensees were prohibited for a number of years from making sheet more than 4 mm thick. Photographic plates, ~1.5 mm thick, which needed to be exceptionally flat but mostly not very large, continued to be made from top quality cylinder glass for a considerable time. Pilkington abandoned manufacture of plate glass in 1967.

The continuous casting of plate glass was also developed independently by Saint Gobain in France, largely by Boudin. Their first patent, granted in 1926, shows the use of two rolls of equal diameter positioned so that the glass has to be carried slightly uphill by the lower roll before passing under the upper one. That patent envisages the upper roll being used to imprint a design on the surface of the glass. Boudin subsequently obtained a considerable number of other patents for refinements of the method.

(3) Float Glass

In the late 1930s, Pilkington was consciously seeking ways of improving the very costly and time-consuming grinding and polishing; other plate glass makers were doubtless thinking about the same problems. Henry Bessemer had patented a considerable number of other patents for refinements of the method.

In 1952, Alastair Pilkington was elected a Fellow of the Royal Society of Chemistry. He had joined the company as a trainee in 1948 after graduating from Cambridge and quickly showed outstanding ability. In 1955, Alastair suggested that it might be possible to fire the glass on molten metal for a variety of reasons, some rather strange, but no one had developed a useful process. In the 1920s, PPG made one unsuccessful experiment to float glass on molten metal, using antimony. In 1952, Alastair Pilkington and Kenneth Bickerstaff as inventors. It describe the flotation of the ribbon of glass on a bath of molten metal, using antimony (Edge107). World War II caused further development work to be deferred.

Around 1950, when grinding and polishing still removed ~20% of the glass, a Pilkington engineer, K. Bickerstaff, was experimenting with using molten tin to support a ribbon of glass at ~600°C. However, the crucial idea for the float process, smoothing of the glass to give mirrorlike surfaces while supported on molten tin, was developed by Alastair Pilkington (1920–1995). Alastair was a very distant relative of the glass-making Pilkingtons who had come to their notice. He had joined the company as a trainee in 1948 after graduating from Cambridge and quickly showed outstanding ability.

In 1952, Alastair suggested that it might be possible to fire the glass on molten metal at ~1000°C then cooled to ~600°C as it passed along the bath. Small-scale pilot plants were built between 1952 and 1955. The first Pilkington float glass patent in 1953 names both Alastair Pilkington and Kenneth Bickerstaff as inventors. It describes the flotation of the ribbon of glass on a bath of molten metal and its lifting off at the cool end of the float bath. The next two patents concern methods of immersing the glass ribbon in a molten metal bath and, thus, suggest that serious problems were encountered with interactions between the glass, the tin, and the atmosphere in the tin bath.

An welcome discovery was that the original process could only make acceptable float glass of one thickness (~6.5 mm), fortunately very close to that which was in greatest demand (0.25 in.). The problems of varying the thickness were therefore studied; another patent granted in 1958 mentions both lateral spreading to equilibrium thickness and the use of angled edge rolls to control width further along the float bath. The use of nonwetted (graphite) edge guides to prevent lateral spreading is given in two patents of 1962.

In 1955, the company had to decide whether to risk building a full-sized float plant or another very expensive twin-grinder installation: the float plant was chosen. This was built at Cowley Hill, St Helens, and brought into operation in May 1957 but did not produce saleable glass until July 1958. That period was a sore trial to Alastair and his colleagues, who had to solve many completely new types of technical problems. Of course, it also was a drain on Pilkington finances, but perseverance eventually paid off. The further work needed to improve the process and find ways of varying the thickness at will proved expensive, and it was 1963 before the process became unerruptedly profitable (Barker114).

At that stage, reaction of the tin that penetrated a very small distance into the bottom surface of the glass caused a microscopic wrinkling of the surface. That in turn gave the surface a slight “bloom,” which had to be removed by a light polish with rouge. Several more years passed before control of the chemistry of the float bath cured that defect and the float process could regularly produce glass with both surfaces having the long-desired perfectly flat fire-polished quality. Pilkington was granted 37 British patents, and numerous foreign patents, for various aspects of the float process in its first 10 years.

The first licensee was PPG, in 1963, and other companies soon followed. Ford, who took a license in 1966, invested much effort in experimental work to reproduce and develop the process as soon as it was announced. For example, Ford, in 1965, applied for a patent on the use of knurled rolls pressing on the upper edges of the ribbon to make thinner glass by stretching (Fig. 22). This work may have helped them in their bargaining when they took out a license from Pilkington. Ford appears to have been the first manufacturer to convert entirely to the float process.

Pilkington quickly discovered that the spout or lipstone, over which the glass flowed onto the tin bath, could not be immersed in the tin because that caused very rapid corrosion at the refractory–tin–glass line of contact. A method of controlling the flow of the glass onto the tin bath from a nonimmersed spout, to avoid corrosion products forming the lower surface of the ribbon, was soon developed (Robinson116).

PPG devised a method of making float glass, announced in 1975, that did not infringe the Pilkington patents. In the PPG process, there is direct contact between the lipstone, the glass, and the tin (McCauley118): solid silica is probably the only refractory having the required properties for that purpose. In this process, the glass flows into the tin bath already close to its final width and thickness, which may decrease the time needed to smooth the surfaces.

Alastair Pilkington was elected a Fellow of the Royal Society in 1969 and knighted in 1970; he published three interesting papers about the development of the float process. By 1976, 21 manufacturers were paying royalties to Pilkington for the use of the float process, and the output of a typical float line had increased from 1000 to 5000 tonnes a week. There are now several dozen float glass plants worldwide, and there are no signs of the float process being superseded. Other interesting accounts are by Hynd and Edge. Schott, in Jena,
Germany, has a small float line making low-expansion borosilicate float glass; this uses mechanical stirring to achieve homogeneity and needs only a very short lehr.

(4) Wired and Patterned Glass
A comprehensive review of the flat glass industry should also include the production of wired glass and rolled patterned glass, both of which have been extensively used in buildings for many years, but these are not treated here. Dralle and Keppeler discussed their early development.

VI. Electric Lamps

(1) Bulbs
At the end of the 19th century, the glass chimney for oil lamps was still a very important domestic article. Besides stabilizing the flame to stop it being blown out by draughts, the chimney controlled the air flow and kept the burner warm enough to ensure vaporization of the oil. However, the oil lamp was becoming obsolete in towns. Gas lamps were widespread but not very efficient and had other disadvantages, such as risk of explosion and toxic fumes.

The possibility of using an electrically heated wire as a lamp was known early in the 19th century. For example, Grove developed a lamp using a platinum filament, platinum having the advantage of not needing protection from oxidation by the air. However, the search for more-efficient lamps using higher filament temperatures continued. J. W. Swan, in England, had demonstrated in 1860 that a carbon filament inside an evacuated glass envelope could make an effective incandescent electric lamp, but he could not then produce a practical product. In the 1870s, Swan turned to photography and invented the dry photographic plate and bromide printing paper. However, he then returned to the problem of electric lamps, and both he and Thomas Edison produced lamps capable of commercial exploitation in 1879. Edison installed the first successful electric lighting system in 1880. The tungsten filament was introduced by General Electric Corporation (GE) in 1913.

There was soon a rapidly increasing market for good quality, thin-walled, seamless bulbs to make incandescent electric lamps and, of course, for tubing to make the other components. The bulbs, like oil lamp chimneys, were therefore made in paste molds, where a film of water, turned to steam by the hot air, was a natural product for mass production. There was soon a rapidly increasing market for good quality, thin-walled, seamless bulbs to make incandescent electric lamps and, of course, for tubing to make the other components. The bulbs, like oil lamp chimneys, were therefore made in paste molds, where a film of water, turned to steam by the hot air, was a natural product for mass production. The long-established technique of rotating the glass in a wet wooden mold gave a circular section and virtually undamaged fire-polished surface without a seam. As the design of the electric lamp bulb soon became standardized, the bulb envelope was a natural product for mass production.

A semiautomatic paste mold machine for blowing lamp bulbs was developed by Chamberlin in 1912 and used by Corning Glass Works. An alternative, the four-arm Empire machine, was patented in 1914 and widely used (Pitt). Turner reported in 1919 that the annual production of lamp bulbs in the United States already exceeded 200 million. Many bulbs were then still made by hand. The American system, using a team of three—a gatherer, a blower, and an unskilled assistant—produced 1200 to 1300 bulbs in 9 h. The British system, each blower working individually, produced about 800 bulbs per worker in 8 h. The Westlake machine, another invention from Toledo, OH, was becoming popular. In 1919, Turner saw, in the United States, 12-arm Westlake machines making 65,000 bulbs/d.

The Westlake machine was intended specifically for electric lamp bulbs. The operation of both the Empire and the Westlake machines is surprisingly similar to that of a glass blower (Fig. 23). At the top of each unit an arm (a pair with the Westlake) can shoot forward into the furnace to gather gobs of glass by suction. On retraction, the gobs are dropped onto the ends of upturned vertical blowpipes and gripped by neck rings. Some preliminary shaping is then done before the blow-pipe unit swings through 180° so that the parisons hang down. The blow molds at the bottom of the machine are raised, closed around the parisons, and the bulbs blown, the blow pipes rotating the entire time. After release from the machine, the tops of the bulbs need to be burned or cracked off.

Unlike the Owens machine, the Westlake machine does not require a rotating pot, because the smaller size of the heads dipped into the glass, the smaller quantities of glass gathered, and the shorter contact times avoid serious chilling of the melt. Another report in 1923 claimed only 45,000 bulbs/d for a Westlake machine with 12 units (24 pipes) and stated that only 11 machines made more than 100 million bulbs/year in the United States (Dralle and Keppeler). Westlake machines continue to be used to produce thin-walled drinking glasses, including stemware.

The ever-expanding market for electric lamp bulbs led Corning to develop a completely new machine for their production. The linear form of Corning ribbon, or 399, machine is unlike any other used for making hollowware. The machine was conceived by W. J. Woods but largely developed by D. E. Gray, Corning's chief engineer, around 1926. The machine (Fig. 24) was so unusual that the patent includes 18 sheets of diagrams as well as 15 pages of text. A continuous stream of glass falls from a forehearth, passes between two rollers, and is turned horizontally as it falls onto a band made up of a series of plates, each with a hole in its center. This method of allow-
(2) Tubing

Tubing has long been made and used as the starting material for many glass products from flashlight bulbs to laboratory wares and industrial chemical plant products. Considerable quantities were needed for the internal parts of incandescent bulbs. Currently, the most familiar use of tubing is in fluorescent lamps. The potential of using luminous discharge in gases, instead of tungsten filaments, for lighting was recognized around 1920. Much effort was expended in developing such lamps from about 1925. This created a rapidly growing market for tubing.

The earliest successful mechanized process, invented by Sievert, Blow heads mounted on a continuous caterpillar track above this band then engage the upper surface of the ribbon and begin to blow. The glass begins to sag; (3) blow heads engage the top of the ribbon and begin to blow; (4) blow molds rise from below and close around the parisons; (5) at the other end of the machine, the blow molds open and drop away; (6) the blow heads are disengaged; and (7) bulbs are then cracked off. Ribbon is crushed and returned as cullet.

Several other tube-drawing processes are used. A process credited to Philips in the Netherlands, otherwise very similar to the Danner process, draws the tubing from the inside of a hollow mandrel. This decreases the possible contamination of the inner surface of the tubing to which phosphors or other coatings may be applied. Several methods for drawing either vertically upward or downward have been patented and exploited, for example by Corning and by Schuller (see Giegerich and Trier).

Since the 1920s, highly refractory tubing has been in demand for special types of lamps. In the early days, high-pressure mercury lamps made severe demands, then high-power tungsten filament lamps were needed for slide and kine projectors as well as searchlights. More recently, the development of quartz–halogen lamps required higher operating temperatures for lamp envelopes than most glasses can provide.

Effective methods of making good quality quartz glass tubing were therefore being sought as early as 1930. The Hänlein process became the standard method.

VII. Optical Glass

Production of optical glass may be considered chiefly a matter of special melting procedures but was not dealt with in the author’s previous centennial review. It deserves inclusion, because it is a separate and very important branch of the industry.

The classic process for making good optical glass by stirring the melt in a pot to homogenize it was invented by a Swiss, P.-L. Guinand, around 1790. On completion of melting, the pot was cooled very slowly, then the cold pot broken open and the best lumps of glass taken for further processing. The process was first brought to commercial success around 1805 by Guinand and Fraunhofer in Bavaria. Guinand soon left that collaboration and resumed manufacture on his own account, continuing until his death in 1824. The manufacture was later carried to France by members of Guinand’s family. One of their collaborators, Georges Bontemps, took the knowledge to Chance Brothers in England in 1848, and Chance Brothers remained a major manufacturer until about 1960, some time after they were acquired by Pilkington; the Chance–Pilkington works has continued to make optical glasses in Britain. In 1931, Hampton and Wheat reported that, despite many investigations of more-complex stirrers, Guinand’s original procedure remained as good as any. That remained the only method until the 1940s.

Until about 1880, the main requirement was for crown and flint glasses to make achromatic doublets. However, the work of Abbe, Schott, and Zeiss in Germany, beginning around 1885 (Everett), soon produced a much wider range of glasses for microscope lenses; Schott continues to be one of the leading manufacturers. World War I made several countries initiate or expand their facilities to replace glasses previously imported from Germany. World War I also increased demands for a wider range of glasses for instruments, such as range finders and binoculars. The rapid development of photography and kinematography soon made further demands on optical glass manufacturers.

The first successful attempt to make optical glass in the United States was, according to Glaze and Chance, undertaken by E. Feil (great-great-grandson of P.-L. Guinand) and G. A. Macbeth in 1888, but their production ended before 1902. Manufacture did not begin again until 1912, when Bausch and Lomb, who had made an agreement with Zeiss in 1908, began their own trials. By 1914, they had achieved some good results, and the National Bureau of Standards also began to work on the manufacture of optical glasses in that year. These two organizations began a close cooperation in 1917 and, from the beginning of 1918, achieved a production of 40 000 lb/month. In England, sales by Chance Brothers averaged almost 20 000 lb/month in 1917.
Two of the least attractive features of the classic method of manufacture were the very slow cooling of the whole pot, which sometimes caused devitrification, and the randomly sized and oddly shaped fragments produced by breaking the pot. The possibility of casting and rolling optical glass in the same way plate glass was investigated by both Bausch and Lomb and by PPG. Such glass, up to 2 in. (~5.1 cm) thick, did not meet the highest standards but was found suitable for many purposes and extensively used by the end of World War I. Because permissible rates of cooling depend inversely on the square of thickness, such cast slabs could be annealed much more quickly than large pots. The Bicheroux method could be used to make slabs up to ~1.5 in. (~3.8 cm) thick, but these contained some striae. However, because the striae were aligned parallel to the surfaces, the glass was suitable for opthalmic purposes.

The methods of making optical glass remained unchanged until the end of World War II. Chance 142 reported that his firm’s yearly production had reached 270 tons in 1942. He also gave some interesting data about average losses at different stages of manufacture, showing that an average of only 27% of the glass melted was finally packed and dispatched (Table III).

Because 45% of the glass was lost by the time that the lumps had been selected, manufacturers attempted to find an alternative to breaking the slowly cooled pot. Considerable effort was therefore put into various techniques of casting and improving both the range and the quality of molded blanks.

Much ingenuity was exercised in attempting to avoid striae caused by pot corrosion products, which almost inevitably contaminated the glass cast from a pot; a Morey 143 patent of 1939 mentions the use of platinum-lined pots. Glasses for some purposes were melted in platinum by Bausch and Lomb between 1945 and 1950 (Glaze 140). Platinum pots were also used in Britain at that time for some refractory glasses made by the General Electric Company (GEC), such as those needed for powerful projector lamps.

Some experiments were done at that time on melting optical glass in tanks, but achieving the necessary homogeneity required the development of a sufficiently effective stirrer. There were also doubts about the ability to sell and use the quantities of glass that a tank would produce. It was at first assumed that changing from one type of glass to another would require complete draining of the tank and cause unacceptably large losses on each changeover to another type of glass.

Various attempts were made to avoid contamination by refractory corrosion products and to achieve good homogeneity by stirring. Thus, in 1941, Hicks and Henkel 144 applied for a patent for a melting unit made of platinum and comprising a V-shaped vessel that could be rotated to mix the glass and then tilted to collect all the glass in one arm for discharge.

The use of a small electrically heated tank, partly lined with platinum and provided with means for vigorous mechanical stirring, seemed to be very attractive. Work at Corning by Erickson and DeVoe led to the design and construction of such a furnace, which was in operation by 1943; that furnace could produce 50 lb/h (~22 kg/h) of optical-quality glass.

A few years later the U.S. Air Force asked Corning to produce much larger blanks of optical glass. That led to further work on a larger furnace having a more complex stirrer developed by De Voe 145 that was fitted at the end of the furnace just before the stream of glass was delivered. Data published by Platt 146 indicate that such a furnace may contain 2500 lb (1.14 tonne) and that the average residence time is only ~7 h. This permitted rapid conversion from one glass to another without draining the tank. This type of furnace has since then been the standard method of making optical glasses as continuously cast slab, usually about 600 mm wide and up to 100 mm thick.

Wright 147 described in detail the development of optical glass manufacture in the United States during World War I. A series of articles by Glaze 140 covered the period up to 1953. The centenary of making optical glass in England occasioned a review by Chance 144 in 1947. A more recent review of modern optical glasses is by Deeg 149.

### Table III. Typical Losses in All Stages of Manufacturing Optical Glass

<table>
<thead>
<tr>
<th>Operation</th>
<th>Percentage loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting</td>
<td>2.5</td>
</tr>
<tr>
<td>Breaking down</td>
<td>25.0</td>
</tr>
<tr>
<td>Trimming</td>
<td>22.0</td>
</tr>
<tr>
<td>Molding</td>
<td>4.5</td>
</tr>
<tr>
<td>Grinding and polishing</td>
<td>11.0</td>
</tr>
<tr>
<td>Sorting</td>
<td>16.0</td>
</tr>
<tr>
<td>Cutting</td>
<td>24.5</td>
</tr>
<tr>
<td>Spindle grinding</td>
<td>2.0</td>
</tr>
<tr>
<td>Remolding</td>
<td>5.0</td>
</tr>
<tr>
<td>Fine annealing</td>
<td>1.0</td>
</tr>
<tr>
<td>Packing</td>
<td>2.0</td>
</tr>
</tbody>
</table>

*After Chance 142.*

### VIII. Glass Fibers

Réaumur recognized some of the interesting properties of glass fibers more than 250 years ago. In the 19th century, slag wool fibers were blown using steam jets and small quantities of novelty fabrics were woven from silk and glass fibers. The first scientific application of very fine silica fibers, extruded by bow and arrow, was by Boys 150 (1855–1944), who needed very delicate but strong perfectly elastic torsional suspensions for sensitive galvanometers. However, successful commercial exploitation of glass fibers seems to have begun in Germany before 1914. A detailed account by von Reis 151 described the need for fiber products in Germany in 1937, their methods of production, and their properties.

In the 1930s, ~4000 tonnes of glass-fiber insulation were being produced annually. As processes improved, so did demand. Industry currently produces millions of tonnes every year, and the range of uses for insulation, filtration, reinforcement, and fabrics keeps steadily increasing.

One of the classic investigations of glass technology, that of Thomas 152 proving that glass strength does not inherently depend on sample size, was done by drawing and testing untouched fibers in a clean atmosphere of low humidity. Fibers for optical communication systems, now a very important application, were discussed by Kurkjian and Prindle 153 in another Centennial Feature.

#### (1) Glass Wool for Insulation

Glass fibers were used in Germany as an asbestos substitute during World War I. The Gossler process for drawing continuous fibers was used by several European companies during the 1920s (von Pazsiczyk 156), but the hanks of straight fibers were unsuitable for bulky, low-density insulation.

Chance Brothers, in England, decided to begin the manufacture of glass silk in 1930 and licensed a process developed by Pollak in Vienna. Callet was heated in an electric furnace from which continuous fibers were drawn out horizontally onto a 3 ft (~0.9 m) diameter rotating drum. This was operated for a few years but proved unsatisfactory for several reasons; corrosion of the refractory drawing orifices was one of the serious problems. Gossler 155 patented the use of a metal lining, clearly intending to use steel, and used downward drawing of the fibers.

In 1933, Slayter and Thomas 156 applied for a patent, not granted until 1938, for the Owens steam-blowing process that used the turbulence of steam jets to extrude the streams of glass falling from orifices and curl the fibers. Such an action follows from the fact that gases and glasses have similar kinematic viscosities at glass-melting temperatures and, therefore, interact. Those fibers naturally formed low-density fine-fiber-wool suitable for insulation or filtration. A related patent 157 describes the use of a metal bushing, winder, and the mechanical drawing of fibers. The Owens process remained the major one for two
decades. The most important developments in this process were the use of platinum-lined bushings and a platinum container that could be heated electrically.

Chance Brothers in England obtained a license for that process in 1935. Early trials by Chance Brothers with fibers later led to establishment of the main British makers of glass-fiber products as a Pilkington subsidiary, Fibreglass, Ltd. Owens–Illinois and Corning continued to cooperate closely during the 1930s, and their success led to the setting up of Owens–Corning in 1938.

Other more efficient methods of producing low-density glass-wool were sought. Both Harford and Stafford,158 employed by A. D. Little in the United States, and Rosengarth and Hager, in Germany, developed ways of making fine curled fibers by dropping a stream of glass onto the center of a rapidly rotating disk. The centrifugally formed fibers were then blown downward and further extruded by a surrounding ring of gas jets. However, that method was not at first as efficient as the Owens steam-blowing process, and it did not initially prosper in the United States, although the Hager159 process was used widely in Europe. The markets for fiber insulation and other uses grew rapidly on both sides of the Atlantic.

After World War II, the search for higher throughputs continued.瓶口技术France and Owens–Corning applied for patents to cover processes that used centrifugal force to form fibers from a multiplicity of holes around the rim of a metal spinner. The streams of glass leaving the spinner were further extruded by encountering annular gas flames directed downward. The Saint Gobain patent of Peychès160 was eventually decided to have priority, and Owens–Corning negotiated a license for that process in 1956. Further French patents for refinements of this process were granted to Peychès, Heymes, Levecque, and Charpentier.161 However, by 1958, Kleist,162 at Owens–Corning, had developed a process that used radiant or radio-frequency heating of the spinner and an annular air blower for attenuation of the fibers. Another patent by Kleist and Snow163 shows all the elements of the successful Owens–Corning process. By the early 1970s, these two processes and variants of them had come to dominate fiber insulation manufacture throughout the world. Although quality and productivity have improved since then, the processes remain essentially the same.

Owens–Corning patented and introduced an important development in 1994 (Houp et al.164) when a new fiber was marketed under the trademark Miraflex. This material of very low bulk density feels similar to natural cotton wool; it is almost entirely free from the irritation of the skin often experienced when glass-fiber insulation is handled. These naturally curled fibers comprise two semicircular sections of glasses having different coefficients of thermal expansion that are sealed together. The fibers are produced by a novel rotary spinner that feeds streams of both glasses to each of the several thousand holes in the spinner.

(2) Continuous Filament and Textiles

Because some hand-woven glass-fibers had been found very useful as electrical insulation, Slater at Owens–Illinois, in 1933, began to explore the possibilities of weaving glass-fiber cloth. By the next year, a method had been developed of gathering steam-blown fibers from a perforated drum or conveyor to form a staple sliver that was wound onto a spool. This was then twisted on a standard textile machine and woven on a hand loom. In 1936, Slater and Thomas found that they could form steam-blown fibers into continuous strands if the steam jets were used only to cool the fibers, not to extrude them. This process gave much finer fibers than the Gossler155 method could produce. Subsequent developments led to the application of coatings during fiber drawing and improved winding of the strand onto the spool.

The modern process using multiple oriﬁces in platinum bushings was invented by Russell165,166 at Owens–Corning and patented in the 1950s. One of the key features was the use of chilled-metal cooling fins to stabilize the hot glass emerging from the orifices. This permitted the number of oriﬁces or tips per bushing to be increased from 102 in the 1930s to 4000 in 1999.

Several books have been devoted to the manufacture and uses of fibers; the most useful are Carroll-Porczyński167 and Loewenstein.168 Recent chapters about fibers are by Aubourg and Wolf169 and by Gupta.170

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Editor’s Note: A photograph and biographical sketch of author Michael Cable can be found as part of an earlier Centennial Feature he authored, “A Century of Developments in Glassmelting Research,” for the May 1998 issue of the Journal of the American Ceramic Society (page 1094). Since publication of that biographical sketch, Dr. Cable received the President’s Award at the 1998 San Francisco International Glass Congress.