Section 11
FLAT GLASS MANUFACTURING PROCESSES
(Update)

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CONTENTS

FIGURES

TABLES

Section 11
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1. Introduction

The flat glass industry has undergone two technological revolutions in the 20th Century. The first of these, occurring in the period between the two World Wars, transformed flat glass manufacture from a batch process to a continuous one and saw the development of several commercially successful sheet glass production techniques, such as the Colburn, the Fourcault and the Pittsburgh processes. In addition, plate glass manufacture was developing to the point of having the technology for continuous twin grinding and polishing of the plate glass ribbon in commercial use by the start of World War II.

The second revolution has taken place in the last 30 years, and is, of course, the development of processes for forming flat glass on a substrate of molten tin, i.e., the development of float glass technology. The story of this development, as told from a historical perspective, and the current state-of-the-art in float glass manufacturing will be the preponderant theme of this section. Other flat glass manufacturing processes (sheet and plate) will not be covered, having been sufficiently treated by R. W. Yunker (p 683) in another part of this book[1]; patterned glass will not be discussed for the same reason. However, the Fusion Process, developed by Corning Glass Works, will be described. While some might prefer an analysis of contemporary float processes only, the historical approach seems, on the whole, justified, since it adds cohesiveness to many aspects of float glass manufacture, and since, for reasons of corporate security, information in the open literature about float glass manufacture, particularly concerning the first two decades of its development, is quite sparse.

That part of the process upon which most discussion will concentrate is the float bath, a remarkable entity which, although first envisioned as a finisher of glass surfaces, also functions as a container, a conveyor, a forming unit, a chemical reactor and a heat exchanger. Engineering aspects, as well as production characteristics, will be covered, but other parts of the process, such as the tank, the lehr and the wareroom will receive minimal attention.

The economic impact of float glass on the manufacture of sheet and plate glass has been profound. This aspect of float will be discussed briefly; finally, an assessment of future trends in float glass manufacture will be attempted.

2. A Brief History of Float Glass

A. Prehistory

Bessemer, in the mid-19th Century, was the first person to recognize the advantages to be gained from forming flat glass by pouring the molten glass onto a liquid metal substrate and then cooling the formed piece until it was dimensionally stable. In his patent[2], he specifies that tin, lead, or bismuth could be used for this purpose, and clearly perceived that some means of providing a reducing atmosphere and/or a technique for dross removal was necessary to achieve a successful forming technique. There is, however, no indication that he followed through with these ideas.

A curious parallel occurred in 1900, when one Luigi Lombardi, a "subject of the King of Italy, residing at Via San Quintino, Turin, Italy," was granted a United States patent[3] for manufacturing flat dielectric plates (for use in capacitors) by pouring a liquid such as wax or paraffin onto another, denser, liquid (e.g., mercury) and allowing the poured liquid to congeal and form a flat plate.

The first U.S. patent describing the manufacture of flat glass by pouring molten glass onto a liquid metal bath and then drawing it along the bath and into an annealing lehr was issued to William Heal[4] in 1902. Heal described means of controlling glass thickness by applying forces to the ribbon and also recognized that glass would stick to the walls of his forming chamber and suggested means for getting around this problem. The compartmentalization of the tin bath to provide temperature control of the glass ribbon was detailed in a U.S. patent by H. K. Hitchcock, in 1905[5].

An early experimental attempt to produce glass on a molten metal substrate was made at the Creighton plant of PPG Industries in the late 1920s. The experiments failed, largely because of difficulties in constructing a basin which would hold the liquid metal (which was not tin, but antimony). These experiments were done on a small-scale, part-time basis at a production facility (a plate glass line) by the plant's chief electrical engineer, and were not pursued further.

B. The Pilkington Success

The great breakthrough in float glass technology was made by Pilkington Brothers (PB) in the 1950s. Starting from a clear, well-defined objective, that of fire-polishing rolled glass on a liquid metal substrate and thus avoiding the grinding and polishing operations, they were able to develop the first commercially successful float glass manufacturing process. The development took seven years of massive effort and expenditure; its success is directly due to the vision and pertinacity of the workers involved and to the patience and economic courage of Pilkington Brothers management.

The problems encountered during these years (and up until about 1962) were primarily of an engineering and chemical nature. It was the solution of these problems that ends the first phase of float glass development. An extremely informative account of this period is given by Pilkington[6].

C. The Maturing Technology (1962–1972)

For the next decade, most activity in float glass manufacture was centered around the licensing of the PB technology by flat glass manufacturers around the world and by the development of techniques for making a float product which was ever thinner and thinner. A process which, in 1965, was seen to be capable of displacing plate glass, was, by 1970, clearly capable of supplanting sheet glass as well. As sizing techniques were developed for the manufacture of 3.0 and then 2.5 mm glass it became clear that the inferiority of sheet glass technologies to float would soon result in their economic demise.

D. Further Expansion

In 1974, PPG announced the development of their own proprietary float-forming process and built the first production line in their Wichita Falls, Texas, plant. Since that time several other PPG process lines have been constructed. By the mid-1980s a reasonable projection envisions two float-forming technologies being used by the companies that developed them and by licensees, producing float glass of comparable quality and markedly superior to any sheet glass which might still be produced.

3. A Brief Description of the Float Processes

At this point it would be appropriate to describe in general terms the PB float process (Figure 11-1). In the PB process[7] glass from the tank flows under a tweel and over a lip (or spout) onto the tin bath. The glass temperature at this point is approximately 1950° F. This value may fluctuate, depending on tonnage and other considerations, but it is always well above the liquidus temperature. The glass follows a very complicated flow pattern in this region of the bath. While the bulk of the glass is flowing forward and laterally to form what is called the "onion", the glass that was in contact with the lip refractory flows in the reverse direction to the "wetback" and thence outwardly and forward to be in the outer edges of the ribbon. It is this wetback flow phenomenon which is at the heart of the PB process and which is described in detail in Pilkington's article[6].

The flat ribbon is pulled by tractive forces coming from the lehr (and possibly from sizing machines); it is this combination of forces which acts to thin the ribbon as it moves downstream. At some point in the bath the ribbon cools to the point of dimensional stability, and it is then conveyed to the annealing lehr, exiting the bath at a temperature of ~1125°F.

The PPG process (Figure 11-2) differs in that the glass passes onto the float bath over a wide threshold made of a material which does not react with the glass to any extent[8]. It passes through a short set of refractory guides and proceeds at essentially constant width downbath with the width and thickness controlled by the lehr and sizing machines. When the ribbon exits the bath, again at about 1125°F, it is annealed, cooled and conveyed to the wareroom.

The difference in the two delivery systems is shown in Figures 11-3 and 11-4. A good comparison of the various characteristics of the two processes has been made by Macauley[9].

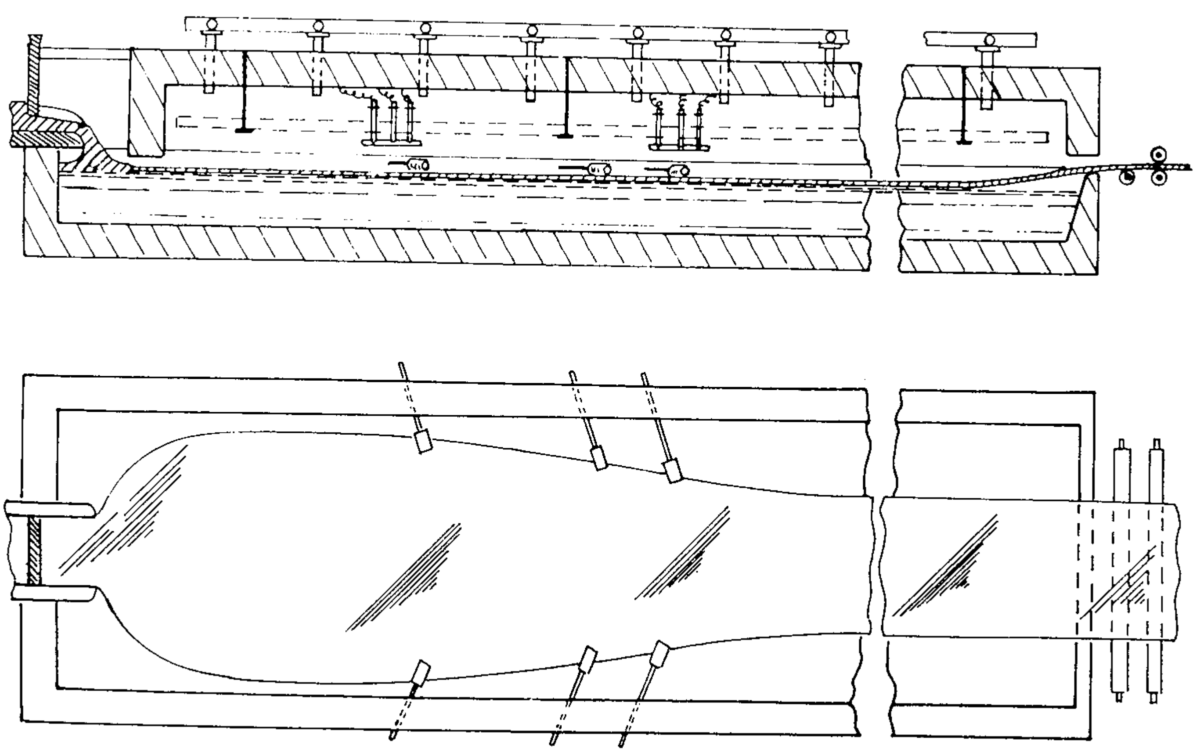


Figure 11-1. The PB float process.

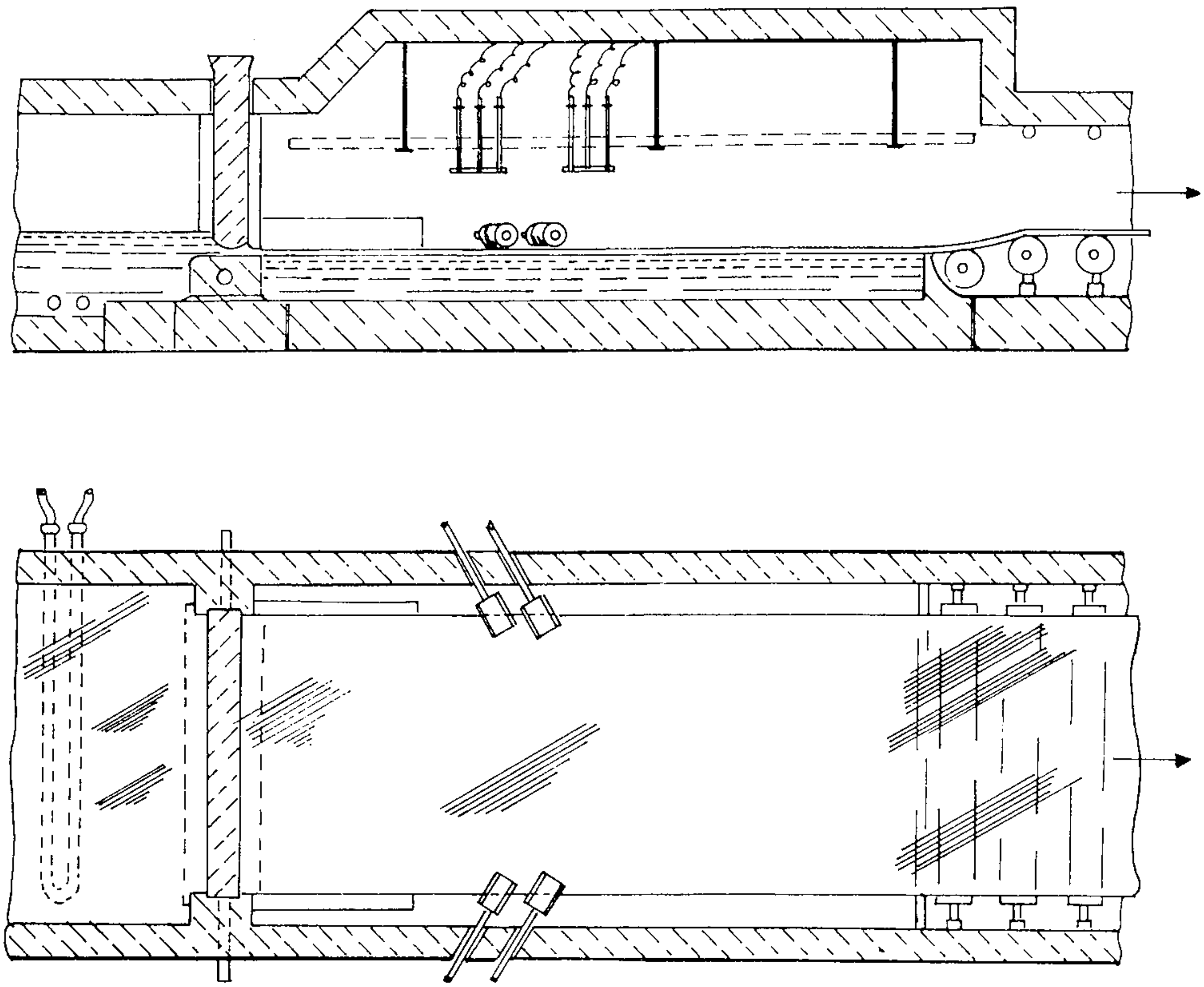


Figure 11–2. The PPG float process.

4. The Float Glass Tank

While not going into detail about a typical float glass tank and without divulging any proprietary practices, a few remarks are in order. A float tank is roughly 30 feet wide, 160 feet long, and holds in excess of 1000 tons of molten glass. The fuel is usually natural gas, often with electric boosting; on occasion fuel oil replaces gas as the main energy source. The overall quality of glass produced is usually quite good, with defects (stones, seeds) that are of tank origin occurring less than once in every 200 square feet of the final ribbon.

Typical glass compositions are shown in Table 11–1. These results were obtained by X-ray fluorescence, and only the major

Table 11–1

Typical Float Glass Compositions[1] (wt%)

	I	II	III	IV
SiO_2	73.08	73.11	72.98	72.65
Al_2O_3	0.10	0.10	0.12	1.15
CaO	8.	8.80	8.40	
MgO	3.86	3.95	3.91	3.94
Na_2O	13.83	13.90	13.76	13.04
MC[2]	0.29	0.37	0.43	0.82

[1]Representative compositions of four major float glass manufacturers
[2]Minor constituents, purposely added or incidental to raw materials used

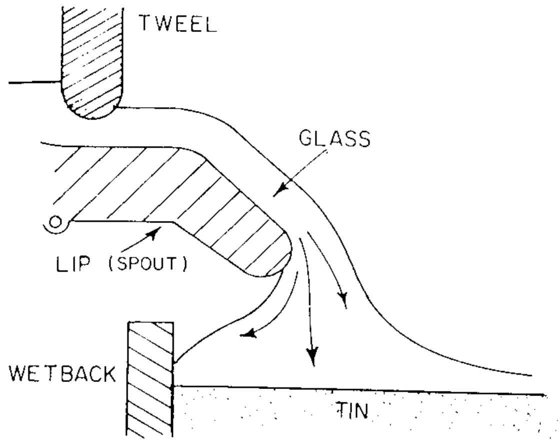


Figure 11-3. PB process delivery system.

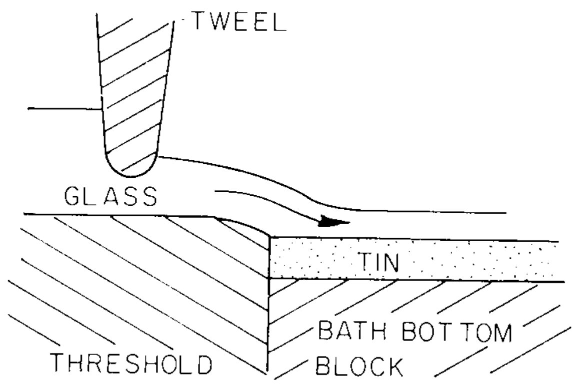


Figure 11-4. PPG process delivery system.

components are shown. The major difference is in the high Al_2O_3 content of the glass IV, which occurs due to its presence as an impurity in the sand supply for Pilkington's Cowley Hill units. Reduction of Al_2O_3 in the U.S. was purposeful for a number of technologic and economic reasons. The above compositions are for clear glass. All manufacturers make a variety of tinted or colored glasses as well.

5. Engineering Aspects of the Float Bath

As mentioned previously, some of the most difficult problems faced by the developers of the PB process at the very beginning were engineering problems. Ask yourself this question: "How can one build a large container that will hold a corrosive molten metal, accept molten glass at one end and deliver it in a semirigid state at the other end, sustain temperature differences of 1000°F from end to end, maintain a non-oxidizing atmosphere throughout, and have provision for heating and cooling the ribbon if needed?" The technical challenge presented comes into perspective, and it is unrealistic to assume anything but an evolutionary approach to such a problem; the float bath of today is the product of such an evolution.

The problem of tin containment has been solved by means of constructing a steel shell, filling it with refractory bath bottom block, not less than eight inches deep, and adding the tin. The refractory provides the necessary thermal gradient between the tin (average temperature ~1500°F) and the steel shell, which is kept at a temperature of ~200°F or less by cooling fans. Since tin freezes at 450°F, the molten tin fills up the cracks between the blocks and freezes, thereby helping to contain the molten tin above it.

Another technique is based on the fact that neither tin nor glass wets graphite. Graphite slabs have been used to cover the bottom blocks, as has graphite powder in the cracks between them, but this practice seems to be dying out. The use of graphite liners along the sides of the bath has also been disclosed[25].

The problem below the glass is one of tin containment; the problem above is that of atmosphere control. The structure which has evolved consists of a large metal shell covering the entire bath and a false ceiling, made of refractory brick, relatively close to the glass. Resistance heaters are located in this ceiling with their electrical connections in the cavity above. The bath atmosphere supply, a mixture of nitrogen and hydrogen, is fed into the roof cavity where it helps to cool the electrical connections as it flows down through the false ceiling into the hotter section of the bath and toward the bath exit. The bath is maintained at a positive pressure to prevent oxygen ingress. With the greatest leakage being at the bath exit, which is covered usually with a refractory fiber curtain adjusted to not touch the glass, bath atmosphere flow rates of 30,000 cfh are not uncommon. A quick calculation shows that an operating tin bath will completely change its atmosphere several times an hour.

The bath refractories deserve further consideration. The original bath bottom refractories were extremely porous and generated vast numbers of bubbles which appeared in the bottom of the ribbon. The problem was alleviated by the installation of vacuum taps on the bath bottom casing, but disappeared altogether with the advent of a second generation block, which was much denser. Unfortunately this block reacted with the sodium migrating from the glass through the tin and into the bottom block, forming what were called "bottom droppers". This problem was solved by a further change in composition. Today's bottom block has good thermal shock resistance, low thermal conductivity, and an exceptionally low tendency to react with any substance present in the bath.

A very special class of bath refractories includes those which come into contact with glass at the forming end of the bath. Since the early 1960s the general trend has been toward longer service life refractories. Lips are now made of fused cast α-β alumina, while tweels are now fused silica.

Another area of current interest is the use of castable materials in place of some bath bottom refractories[26]. The cost savings are considerable, and it appears that no degradation in bath performance is observed when castables are used. This area will be one of considerable activity for the next decade.

6. Float Bath Chemistry

The subject of float bath chemistry is so vast that many chapters could be spent on this subject alone. What follows is a selective survey of some of the more important areas, including criteria for selecting a proper liquid metal, the concept of an equilibrium thickness, the oxygen and sulfur cycles, and some comments about the concentration profiles present in the glass.

A. Proper Liquid Metal

When one lists the conditions that the supporting metal for the glass must satisfy, it is clear that there will be few materials that qualify[10]. Some of these criteria are that the material must:

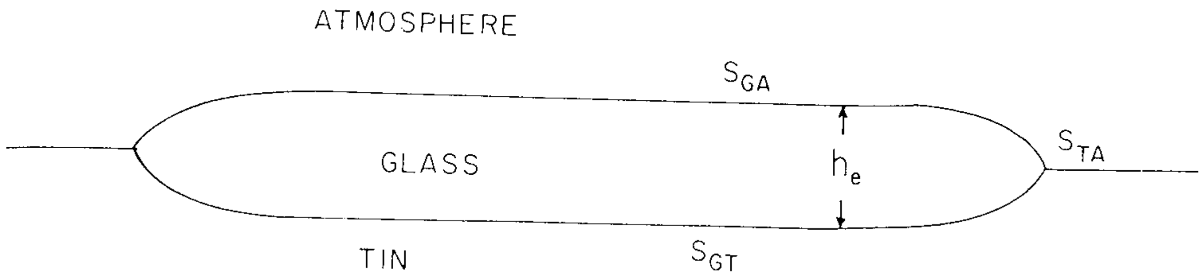
(1) be a liquid from 1000°F to 2000°F
(2) be denser than glass
(3) have a low vapor pressure, and
(4) be relatively unreactive with glass.

Immediately, it is seen that only liquid metals could be considered as serious candidates, and of the appropriate metals conditions (3) and (4) leave gallium, tin and indium as the only choices. If a further constraint, namely that of material cost, is applied, then tin becomes the choice. There are some alloys of tin which are also usable, but no clear advantage emerges. It appears that for the near future tin will be the standard float bath metal unless a catastrophic rise in price or drop in supply should necessitate the use of a cheaper or more available alloy.

B. Equilibrium Thickness Concept

The early finishing experiments done by Pilkington exhibited an unusual phenomenon: when glass of any thickness was rolled onto the float bath, glass of slightly less than 7 mm thickness was produced. This curious result was due to the fact that while gravitational forces tend to spread the glass, there is also a surface tension effect which tends to contract it. As a result there is a thickness at which a mechanical equilibrium is established between these gravitational and surface tension forces. This situation is shown in Figure 11-5; the equation relating the forces was first derived by Langmuir[11].

The existence of this equilibrium thickness has several consequences, the most direct being that glass of 6 or 7 mm thickness should be relatively easy to produce. An-



$$h_e = \left\{ (S_{GA} + S_{GT} - S_{TA}) \frac{2\rho_T}{g\rho_G(\rho_T - \rho_G)} \right\}^{1/2}$$

Figure 11–5. Equilibrium thickness concept.

other implication is that if one could somehow change the value of the equilibrium thickness to, say, 3 mm, then 3 mm glass should be easily made. Many different approaches have been tried, e.g., pressurization, molten salts, alloying the tin, changing glass composition, etc., with little or no success. The problem seems to be that only the individual surface tension values are available to change, and they are either insensitive to the parameter being varied or they all change in the same way. In any event, the increased expertise in sizing gained over the past 15 years has relegated these ingenious approaches to technological obscurity.

A third, and more practical, effect of the surface tension forces is that there is a lower limit to the viscosity (an upper limit to the temperature) at which glass can be attenuated successfully. Since the glass is always "growing back" to equilibrium thickness as long as it is on the bath, the only controllable parameter is the rate at which this growback takes place. Fortunately this rate is inversely proportional to the glass viscosity; a rule of thumb for any sizing scheme is that, for the PPG glass composition, growback is unimportant below 1700°F, which temperature then also serves as the upper temperature limit at which much attenuation can be accomplished.

C. Oxygen Cycle

Figure 11-6 shows some of the chemical species involving oxygen which occur in a float bath. The sources of oxygen are from air leaks into the bath, contamination of the atmosphere supply, and the molten glass. In early float production units oxygen was present in sufficient quantity to cause the formation of SnO_2 dross on the metal surface and to contribute to a bottom surface phenomenon called "bloom". As the float bath crews gained operating experience they discovered more efficient bath sealing techniques; as the air leaks were reduced, the oxygen concentrations dropped as did the SnO_2 and the tendency to bloom. This also was a strong indication that the ribbon itself was not a major source of oxygen. In to-

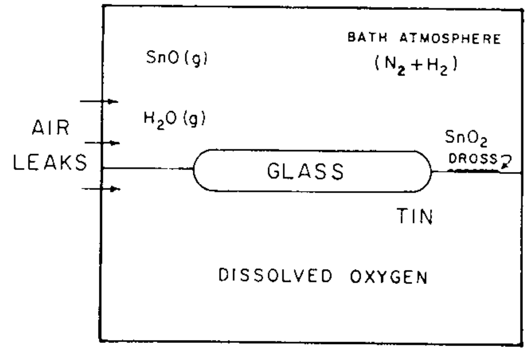


Figure 11–6. Oxygen in the float bath.

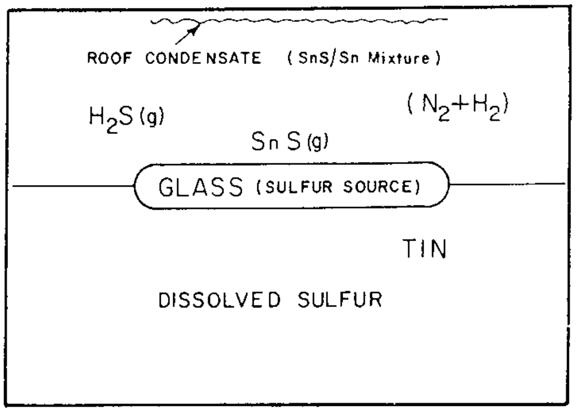


Figure 11–7. Sulfur in the float bath.

day's operations, despite the complexity of the oxygen chemistry, the oxygen cycle is rarely a problem.

D. Sulfur Cycle

Figure 11-7 shows the sulfur analog of Figure 11-6. While simpler than the oxygen cycle, with the ribbon being the only source of sulfur, it nevertheless poses an operating problem since the SnS vapor condenses on portions of the bath roof and unused heating elements and ultimately is reduced to tin, which then is dislodged, falling onto the ribbon and causing a "top drip" defect. One way of reducing this problem is to dislodge the accumulated material by heating up that portion of the bath where it is located and accelerating the reduction process; another alternative is to "blow down" the bath roof using an atmosphere lance. The use of these technologies in any combination results in the glass being discarded temperarily as this "cleaning" takes place.

As the levels of tank-related defects have continued to decrease, the top drip defect has become a more significant defect source. The most beneficial means of combating it has been that since, for environmental reasons, the amount of sodium sulfate added to the batch has been greatly reduced over the past decade, the sulfur cycle and the problems caused by it have become less troublesome.

E. Compositional Gradients in the Float Ribbon

The concentration profiles of float glass near the surface show many interesting features. The penetration of tin can be up to 20 into the bottom surface of float glass. In addition Sieger[12] has measured the composition gradients of sodium, calcium, sulfur and iron near the glass surface. This is a field which is just developing as analytical techniques for surfaces become more sophisticated. The first hundred angstroms of the surface, in particular, are of a totally different composition than the bulk; for example Baitinger, French and Swarts[13] estimated that the glass composition at the surface of float glass was in excess of 30 weight percent tin oxide. While many important research results can be anticipated in the next several years, there is one basic problem which is always present, namely, the extreme difficulty of determining the time-temperature history of the samples being studied. Nevertheless, information relative to such problems as weatherability, staining, film formation, and other surface effects will receive more attention in the future.

7. Principles of Float-Forming

A. Development of Sizing Technology

As was stated previously, if the early phase of Pilkington's development of float glass was characterized by the solution of many difficult engineering and chemical problems, the second phase emphasized the development of sizing technology. Again the literature contains few references to this subject; Charnock[14,15] has given a good description of the early development of the technology with emphasis on the physical principles involved, while Narayanaswamy[16,17] has recently discussed later developments, with the emphasis being more mathematical and oriented toward the development of computer simulation of the float-forming process.

It is fortunate that the first float glass product was of a thickness to satisfy the plate glass market (~6.5 mm). This glass was produced by pouring the glass onto the tin, allowing it to stabilize and to relax out any surface irregularities, and then pulling slightly on the ribbon so that the final product was the desired thickness. This "direct stretch" process, a direct descendant of the process described by Heal[4], was merely the first step in a series of developments which resulted in producing even thinner glass products. The forces acting on the ribbon were extremely small; in fact, probably no flat glass has ever been produced so gently. Glass as thin as 4 mm was made in this manner.

The process did have some disadvantages, however. With nothing contacting the glass as it traversed the bath, ribbon stability was a problem as the ribbon was free to respond to any variation in temperature, particularly lateral variations. Also, varying the temperature was the only means of controlling the sizing process on the bath at a given line speed.

There was developed rather quickly a superior technique for sizing — the edge roll process (Figure 11-8). In this process the glass was poured onto the bath, where it formed the onion and cooled as it proceeded to the edge rolls, which gripped the ribbon between two rotating wheels. The bulk of the attenuation then took place downstream of the edge rolls where the glass was reheated, became less viscous, and was more easily attenuated. (The temperatures given in Figure 11-8 are characteristic of the edge roll process.) The ribbon was then cooled and conveyed to the lehr.

Glass of adequate optical quality was produced in this manner, and the edge roll process became the standard of the industry. By about 1970, however, some of its process disadvantages were coming into clearer focus as well. These included the following:

(1) The edge roll machines were large and quite cumbersome; in addition they were installed at a fixed point in any float bath and repositioning them was a major undertaking.

(2) The large ribbon collapse which occurred in the production of 3 mm thicknesses caused problems in the wareroom due to the narrow ribbon and the high line speeds, and precluded the manufacture of 2.5 mm glass by this means.

(3) The early float baths were over-de-

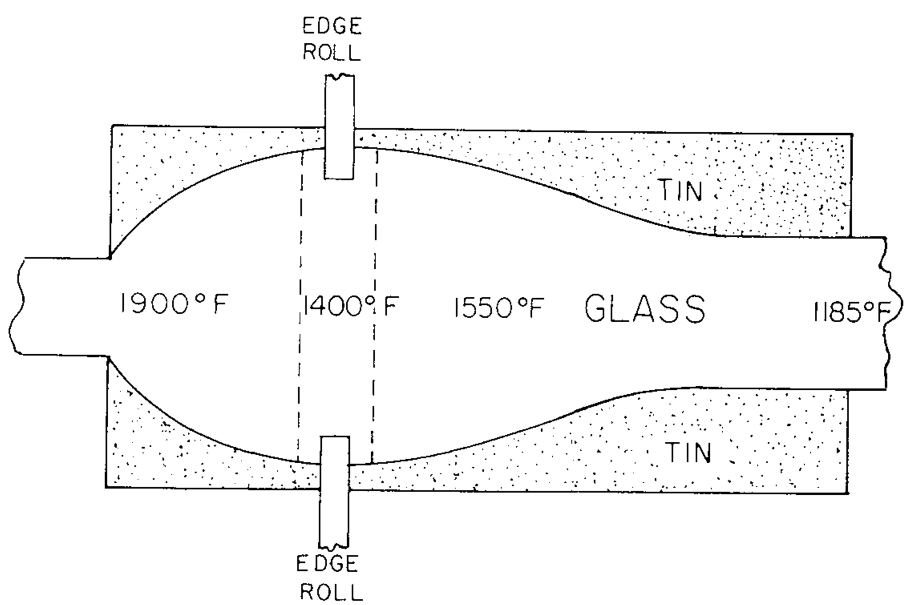


Figure 11–8. PB edge roll process.

signed in the sense that they could process more glass than their associated tanks could produce. As tank technology improved and tank throughput rose the cooling requirements for the bath became more severe. In particular, the heat added in the reheat zone became more of an operational problem, with the result that the reheat was decreased and shifted upstream, putting the edge rolls in the wrong location.

One solution to these problems was the assisted direct stretch process, depicted (schematically) by Pilkington[27]. In this process the edge rolls are replaced by multiple pairs of smaller and more mobile top roll machines, which are positioned at appropriate points in the bath. The single water-cooled toothed wheel on each machine grips the top surface of the ribbon near its edge, and ribbon width is controlled throughout the sizing region, so that a final ribbon width suitable for wareroom processing can be produced economically.

The development of the assisted direct stretch process sounded the death knell for sheet glass manufacture in the United States. With the breakthrough to sheet glass thicknesses the float process which had started as a finishing technique to replace plate glass had become a drawing process which replaced sheet glass as well. Today nearly all float glass manufacturers use variations of the assisted direct stretch process as their standard production technology.

B. Operating Principles for a Float Bath

To visualize the early stages of a float-forming process, consider that, by Newton's Third Law, some form of "anchor" is needed to provide process stability and to provide the vehicle against which the forces of attenuation can operate. In the Pittsburgh process for making sheet glass the drawbar is the anchor. In a float-forming process the anchor could be refractories in contact with glass at the upstream end of the bath, or it could be a portion of the glass itself, as in the edge roll process where the colder glass between the edge rolls forms a "stiff beam" against which the attenuation forces can act. In principle, one could establish criteria which the ideal float-forming anchor should possess:

(1) The anchor should be a transverse strip of the glass ribbon or a piece of refractory material.

(2) At this point in the forming chamber the ribbon should be of a sufficiently high viscosity to sustain deformation stresses, but glass upstream of this point should be hotter, thus preventing the further transmission of these same stresses.

(3) This anchor should have no lateral temperature or thickness variations.

In practice, such an idealization does not exist; lateral temperature variations and velocity gradients are always present. In production, a significant part of any attenuation strategy is to adopt means for eliminating or at least minimizing these gradients prior to the bulk of the attenuation taking place.

In the PB float process, the complex, three-dimensional velocity field that exists in the delivery region is at variance with the desired velocity field for the ribbon in the attenuation zone. Thus a goal in this process is to reorient the velocity of those elements of glass which appear in the final ribbon; this is a major function of the onion. On the other hand, the PPG process, because of its wide delivery system and the absence of free fall, delivers glass with a velocity distribution much more consistent with the target field. Thus the need for an onion, or spread, is diminished. There is, however, a requirement that care must be paid to the chemistry of the glass/refractory interface when achieving velocity alignment by producing wide delivery.

The existence of temperature variations is also unavoidable. In the PB process, as glass flows through the canal, it is losing heat through the canal sides and bottom, thereby amplifying the velocity gradient which would be present in the canal even if the glass viscosity were not so strongly dependent on temperature. PPG's process, with a much shorter and wider delivery system, provides the opportunity to reduce these thermal gradients. In practice, this results in a smaller required region of the bath for homogenization. Measurements taken of the lateral temperature variations downstream of this region on both processes show little difference in practice.

Thickness variations in the lateral direction occur as a result of the temperature and velocity gradients. If these gradients are sufficiently large, as the ribbon is attenuated, the usually hotter center will stretch to a greater extent than the colder sides, and the thickness variation will be increased.

The major processing problem in this region of the bath is thus seen to be one of establishing a uniform temperature and thickness across the glass ribbon. There are two general ways that lateral temperature gradient reduction can be accomplished; one is to heat the colder sides of the ribbon, usually by means of the heating elements which are located in all float baths; the other is to preferentially cool the center, the most common means being the use of radiant coolers (water-cooled steel pipes) placed over the ribbon. Both methods have disadvantages; any heat added will eventually have to be removed before the ribbon exits the bath, as discussed previously; this drawback is particularly debilitating when a bath is operating at high tonnages. On the other hand, the use of radiant cooling is probably a source of optical distortion in the final product. Nevertheless, homogenization must take place, despite the empirical fact that any operational steps which benefit lateral thermal uniformity (and hence thickness variations) will probably degrade the ribbon's optical quality. It is the judicious balancing of these conflicting effects that constitutes a successful operational strategy.

There are differences in sizing strategy between the two float processes, but both sets of procedures are subject to the same physical principles, some of which are:

(1) A necessary, but not sufficient, prerequisite for the production of high optical quality thin glass by any sizing technique is that the thick glass entering the sizing region must be of high optical quality; you cannot produce high quality thin glass from poor quality thick glass.

(2) The sizing process usually worsens the initial thickness contour; a key point in the sizing strategy is to minimize this effect.

(3) Of the four operating variables in the sizing region — ribbon width, thickness, velocity and temperature — only two are independent; having specified these two, the other two are uniquely determined.

(4) The ribbon will flow in such a way as to minimize the work of viscous dissipation done on it.

The more successful a float process operator is in following these rules, the more successful will the process be. As with any process, there are countless ways available for operating improperly; what is needed has been termed bath discipline, which means a careful attention to detail. In float processes this is particularly true when one realizes the small forces which are sufficient to move the entire ribbon around on a tin bath surface.

C. Production of Thicker-Than-Equilibrium Glass

The manufacture of float glass which is thicker than 7 mm has bred a technology of its own[18]. In this case the glass wants to flow outwardly; the Pilkington technique for preventing this is to constrain the glass to flow between non-wetting water-cooled graphite guides; by the time the glass exits from between the guides, it is cold enough to form a dimensionally stable sheet. This process, while not a major production item for anyone, is one of the simplest of the float forming processes in current use. In one sense it could be viewed as a working version of the concepts discussed by Heal in 1902. Most operating problems associated with the production of thick glass are extraneous to the bath and are related to the annealing, cutting and handling of these pieces. Glass as thick as 25 mm has been produced by this method.

8. Equipment and Instrumentation

The float bath represents a particularly alien chemical environment combining high temperatures, highly reactive gases and a corrosive molten metal. As a result, the number of materials which can be used in this environment is limited, particularly the non-ceramic materials. This section will cover in a very general way the types of non-ceramic materials which can be used in a float bath; the techniques and difficulties of obtaining meaningful measurements will also be discussed.

A. Equipment

There is no metal which can be fabricated into equipment for placement into the bath. The high temperatures exceed the use temperatures of most steels (particularly in the hot end) while tin is chemically corrosive to most refractory metals and alloys. Of these latter, tungsten is not attacked chemically by tin, but its cost and the difficulties of fabrication have prevented its widespread use. Certain tungsten alloys show promise but each improvement in machinability (for example) seems to be offset by increased chemical attack by the tin. Until some new material is developed, the basic component for tin bath equipment will continue to be tubular steel, which must be water-cooled, or insulated, or both, before being put into the bath environment.

While graphite looks promising because of the reducing environment, and, in fact, is used to some extent (bath liners, fences, etc.) uncooled graphite is eventually consumed by reaction with bath oxygen. Hollow graphite pieces with water-cooled steel inside them do, however, have a long service life. One would hope that in the next decade some materials or techniques could be developed which would add to this limited assortment of usable tin bath equipment.

B. Instrumentation

There is an obvious need, from a standpoint of bath process analysis and process control, to measure the conditions inside the float bath; the most important process variables are temperatures, ribbon widths and velocities.

Any thermocouple placed directly in the tin bath will dissolve rapidly in the tin. The most common approach has been to place the thermocouple in a ceramic sheath and then to install the unit into the open tin along the side of the bath. From the process control standpoint this is acceptable, in that a reproducible parameter is measured. From the process analysis point of view it is not, for the following reasons:

(1) The temperature measured is the temperature of the sheath and not of the tin or the glass.

(2) There is no uniform practice relative to positioning the thermocouple in the tin (or above it).

(3) Even if accurate, the measurement of the temperature of open tin on the side of the bath may have little relevance to glass or tin temperatures in the center.

The use of optical pyrometers offers one solution to this problem, and pyrometers mounted in the bath roof over the bath centerline have yielded valuable information; but such installations are not free of problems — they are relatively expensive, they require constant maintenance, and, because they are cooled, they can function as a defect source for top drip. The best means at present seems to be a shielded thermocouple mounted over the glass, or, if temperatures are needed in more locations, the use of a portable optical pyrometer, cantilevered over the ribbon and removed when the measurements have been taken is recommended.

The measurement of ribbon velocities is more difficult and is not done on a routine basis. There are two techniques which have been used:

(1) The sand trace method, where an open straight tube is filled with sand and extended over the ribbon perpendicular to the bath side; the sand is then dumped onto the ribbon.

(2) The direct method, where a ball of refractory fiber is dropped onto the ribbon, and the time it takes to pass certain viewing points in the bath (usually located near the top roll machines) is recorded.

Method 1 is seldom used, as it requires the collection of the glass samples at the cutting station and rarely yields unambiguous information. Method 2 is more direct and less time-consuming, and, although it generates average velocities (as opposed to instantaneous velocities), yields the greatest amount of useful information.

The measurement of ribbon width, particularly at the machine locations, is routine.

If the measurement of glass velocities is difficult, the meaningful measurement of tin velocities is close to impossible. There is no area of float technology which is as little understood as the tin flow system. Only when massive changes to the bath operation are made (such as the installation of submerged barriers to tin flow or the use of linear motors to move tin) can meaningful inferences be drawn. It is to be hoped that the instrumentation for measuring local velocities in the tin and in the glass will be developed in the near future.

9. Float Glass Quality

A. Defects

The occurrence of certain discrete defects in the float ribbon has been touched upon in previous sections and is covered in some detail in the article by Pilkington[19]. In this section, the most commonly encountered defects will be discussed from the perspective of their current status as a quality problem; tank-related defects will not be included. The most common defects in float glass which are traceable to the tin bath are bloom, exit end scratches, open bottom bubbles, bath stones, tin oxide, top drip and tin pickup.

Bloom is the occurrence of a haze on the bottom surface of the float ribbon upon reheating to 1200°F. It is caused by the presence of too much oxygen in the bath. The tin in the bottom surface of the glass oxidizes to the stannic state upon later heat treatment; the surface becomes wrinkled, causing the appearance of the haze. Bloom is rarely a problem; most float baths are operated with good atmosphere control and bath sealing; only upon the initial startup of a line or after a bath upset should the glass exhibit the bloom property.

Exit end scratches can occur on either the top or bottom surface of the ribbon. Their cause is the mechanical dragging of the bath exit curtain on the top surface of the semirigid glass or the glass bottom surface grazing the exit end refractory. In either case the remedy is simple: raise the exit curtain off the glass and/or raise the bath exit rolls until the bottom surface clears the exit lip. Other possibilities for correcting exit end scratches on the bottom surface are to raise the tin level in the bath or to lower the exit end temperature. This last remedy would be done with great reluctance on an operating line as bath personnel use this temperature as a primary control parameter, and lowering it increases the possibility of the ribbon fracturing at the exit end, and causing a bath upset.

The occurrence of large open bottom bubbles can be a serious problem. These bubbles can come from any number of sources. The most troublesome variety of open bottom bubble is associated with the deterioration of a bath component located under the ribbon. If this is the case, the defect may persist until the end of the operating campaign.

Occasionally some very small stones will appear on the bottom surface of the ribbon. The source is stagnant glass, most often in the region of the wetback flow, which has gone below the liquidus temperature and has begun to devitrify. The problem can be eliminated by raising the glass temperature in the wetback region or by replacing the refractories (certainly a less popular alternative).

Tin oxide, because of the strong temperature dependence of its solubility in molten tin[20], can occasionally accumulate against the exit end lip and be mechanically dragged away by the ribbon as it exits the bath. In the process the ribbon is mechanically marked and the tin oxide is deposited on the exit rolls where it builds up and causes further bottom surface marking. When this occurs, the accumulated dross is physically removed from the exit end and the exit rolls are cleaned off.

Top drip has been discussed previously, in section 6. It is the most common type of bath-related defect.

One of the most important qualities of tin is that it does not wet glass, as, for example, does molten aluminum. On occasions, however, this nonwettability disappears, and tin is picked up by the ribbon as it leaves the bath. The usual reason for the occurrence of tin pickup is either a lack of cleanliness at the exit end or the contamination of the tin with certain metals (e.g., Al, Ca, Mg and Cr). When tin pickup occurs, it will continue until the bath cleans itself by oxidizing these metals and removing the dross either with the ribbon or by skimming; however, this process is troublesome and may take a prohibitively long time.

While the preceding paragraphs may seem to be an unduly protracted litany of things that can go wrong in a float bath, it should be remembered that the overall quality of the float ribbon is good relative to defect levels; in fact the appearance, on the average, of one defect in 200 square feet of final product will constitute an uncomfortably high defect density for an operating line.

B. Optical Quality

In the first years of float glass manufacture the optical quality of the product was purported to be equivalent to that of plate glass. For the thicker product, which was used primarily in the manufacture of mirrors and automotive backlights, this was by and large true, with the difference so small as to be of no commercial significance. On the other hand, the quality of the early 3 mm float glass fell short of the so-called "North American standards" which applied to plate glass manufacture for use in automotive windshields. It took the better part of a decade before float was able to substantially replace 3 mm plate glass in the automotive market.

The comparison of float and sheet glass shows float to be superior optically at all thicknesses. In fact, float glass produced under conditions which yield glass of "poor" optical quality is still markedly superior to high quality sheet glass.

The optical distortion in float glass is caused by small thickness variations in the glass which act as lenses and form alternating light and dark parallel bands when viewed in a shadowgraph projection (an arrangement in which a point source of light shines through the piece of glass and the image, or shadow, is projected onto a vertical surface). These bands are largely in the process direction, and are similar to but less intense than the distortion pattern in sheet glass. The pattern is called "broken line" distortion, because the bands are of finite length, such length being many times the distance between neighboring bands. While other distortion patterns have appeared from time to time, broken line distortion is the predominant feature of float glass currently being produced.

The lenses which cause this distortion are made up of thickness variations, across the ribbon, whose amplitude is about 50 microinches and whose characteristic wavelength is approximately 2 inches. These variations are caused by the tractive forces of attenuation that must, of necessity, act on the ribbon to make it thinner; some distortion may also be induced in the process of cooling the ribbon. As a general rule, the thickness variations present in float glass (and hence the optical distortion associated with them) will increase as the glass becomes thinner or as the throughput of the line is increased.

All glass manufacturers use slightly different methods of measuring distortion quality, making it more difficult to establish industry standards. One test, which is still used, is the "zebra" board, where a board consisting of black and white diagonal stripes is viewed through the glass at a fixed distance. The distortion is then measured by the angle between the plane of the glass and the plane of the zebra board at which distortion of the stripes first appears.

The human factor present in a measurement of zebra angle is eliminated when the glass is scanned by an optical device and the resulting signal processed electronically. There has been a trend over the past decade to this approach, and instruments with high sensitivity and excellent reproducibility have been developed. While electronic instrumentation varies among float manufacturers, they are competing for the same markets and the distortion quality of the glass sold by them is comparable.

10. Films

One of the major trends in flat glass manufacture in the past 10 years has been toward producing value-added products. A large number of these products are targeted toward the markets for architectural and environmental glass and consist of float glass (clear or colored) to which films possessing desirable spectral properties have been added.

These films can be applied to the glass by various means. Use of vacuum deposition is quite widespread; electroless (non-electrolytic) deposition from solution is also commercially successful. To discuss either method is beyond the scope of this article, but there are two other techniques of applying films to glass which are not.

One of these is the electrofloat process, developed by Pilkington Brothers in the years prior to 1970. In this process, a copper anode traps a copper/lead alloy between it and the float ribbon at a point inside the float bath. When voltage is applied the copper and lead diffuse into the top surface of the ribbon (sodium diffuses out from the bottom to maintain electrical neutrality). The copper and lead are reduced by the action of the bath hydrogen and then agglomerate to form colloidal particles. The resulting product absorbs and scatters light and in general acts as a film on the surface of the glass. A good account of this process is given by Yates[12]; considering the conditions and process operations the development of Spectrafloat (the product name) must be regarded as one of the major technological successes in flat glass in the past 15 years.

PPG has also developed a process for depositing a film on hot float glass[22]. The film deposition takes place in a hood just after the glass exits the float bath; a film of transition metal oxides is formed on the glass by pyrolysis before the ribbon enters the lehr. This product, SOLARCOOL® glass, has gained widespread acceptance as an architectural and automotive product.

11. Economic Impact of Float Glass

If the technological impact of float glass has dominated flat glass manufacture for the past two decades, the economic impact has been equally significant. In the United States, for example, PPG was the first flat glass manufacturer to be licensed to use the float process (1962); other manufacturers followed in rapid succession (note listing, p 712)[23]. The results of this activity can be seen in Figure 11-9, which gives the total production (estimated from various sources) of flat glass in the United States from 1964 through 1980. The bottom curve represents the annual production of float glass; the second represents float and plate production combined, while the top line is the annual flat glass production in millions of square feet for plate, float and sheet glass combined.

Several points are evident. First, float glass replaced plate glass just about as fast as the new float plants could be built. Secondly, while total flat glass production fell in the recession of 1974–1975, float production actually increased, with the older and less efficient sheet plants closing down. This data is presented in a slightly different way in Figure 11-10, where the various market shares are expressed as a percent of the whole, thus eliminating annual fluctuations in production. This graph shows the process even more dramatically. Fifteen years is certainly not a long period of time for technological revolution to take place in a heavy industry, but Figures 11-9 and 11-10 show that in the case of float glass the revolution is clearly over.

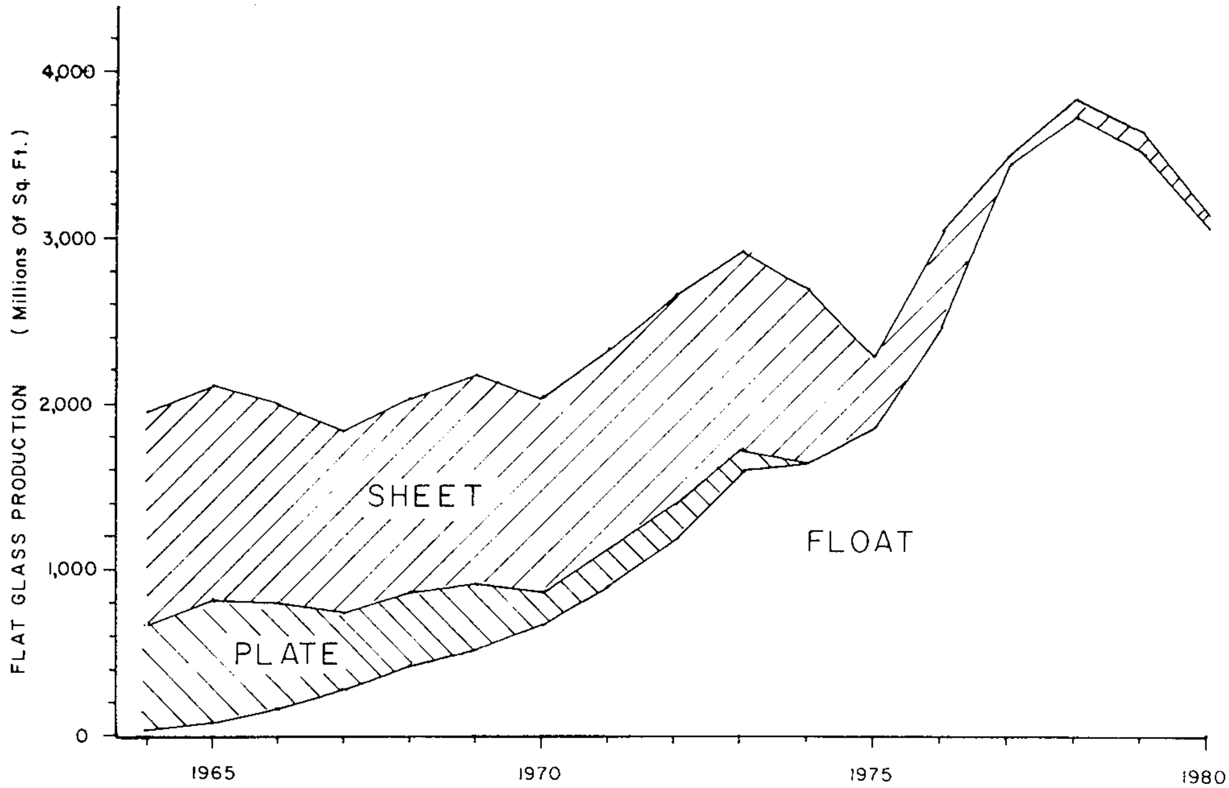


Figure 11–9. Flat glass production in the United States 1964–1980.

12. Fusion Process

There are certain markets which are as yet beyond the reach of float technology.

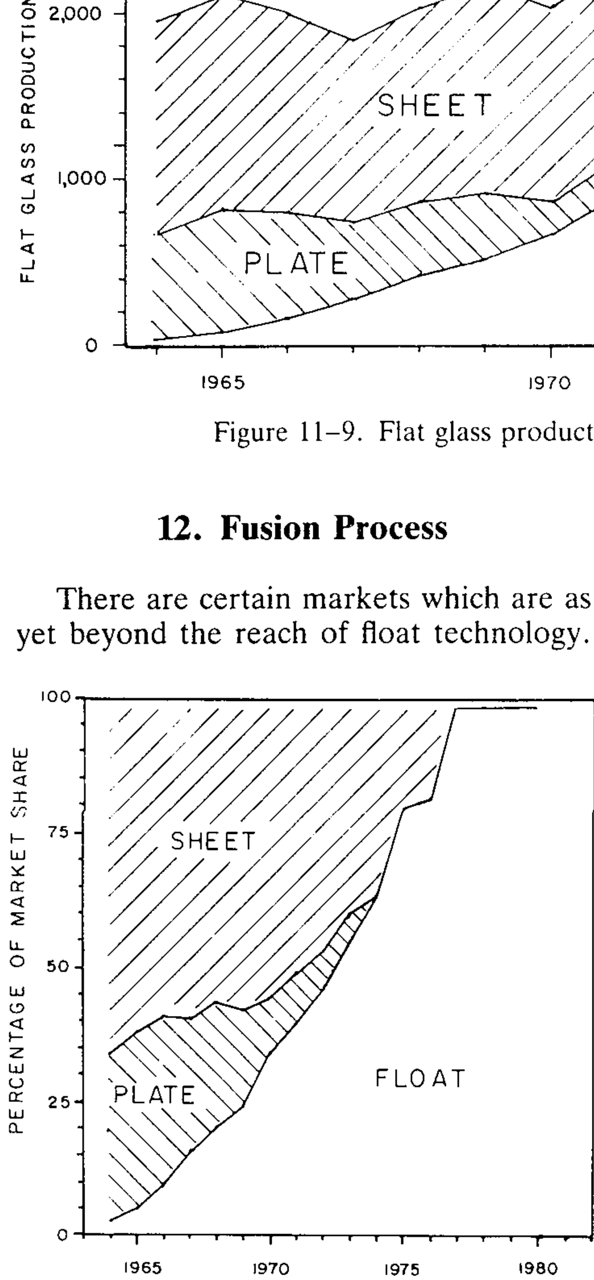


Figure 11–10. Market share of flat glass processes in the United States, 1964–1980.

These are the markets for unusually thin glass (e.g., 0.040 inch), small sizes (microscope slides), or unusual compositions, to name just a few possibilities. One process which is attractive for the manufacture of such products is the Fusion Process, developed by Corning Glass Works, which is a downdraw method of drawing high quality sheet glass from a variety of glasses. It is particularly well suited for producing thin sheet.

Figure 11-11 illustrates the basic concept of the process. Well-stirred hot glass is delivered through suitable conduit tubes to one end of a rectangular trough. Typically the viscosity of the glass is 40,000 poises at this point. The upper edges or weirs of the trough are slightly inclined downward from the inlet end and cooperate with the upwardly inclined trough bottom in such a way that the pressure drop is linear with distance along the trough. The glass overflows the weirs evenly along the full length of the trough, runs down the sides, and the

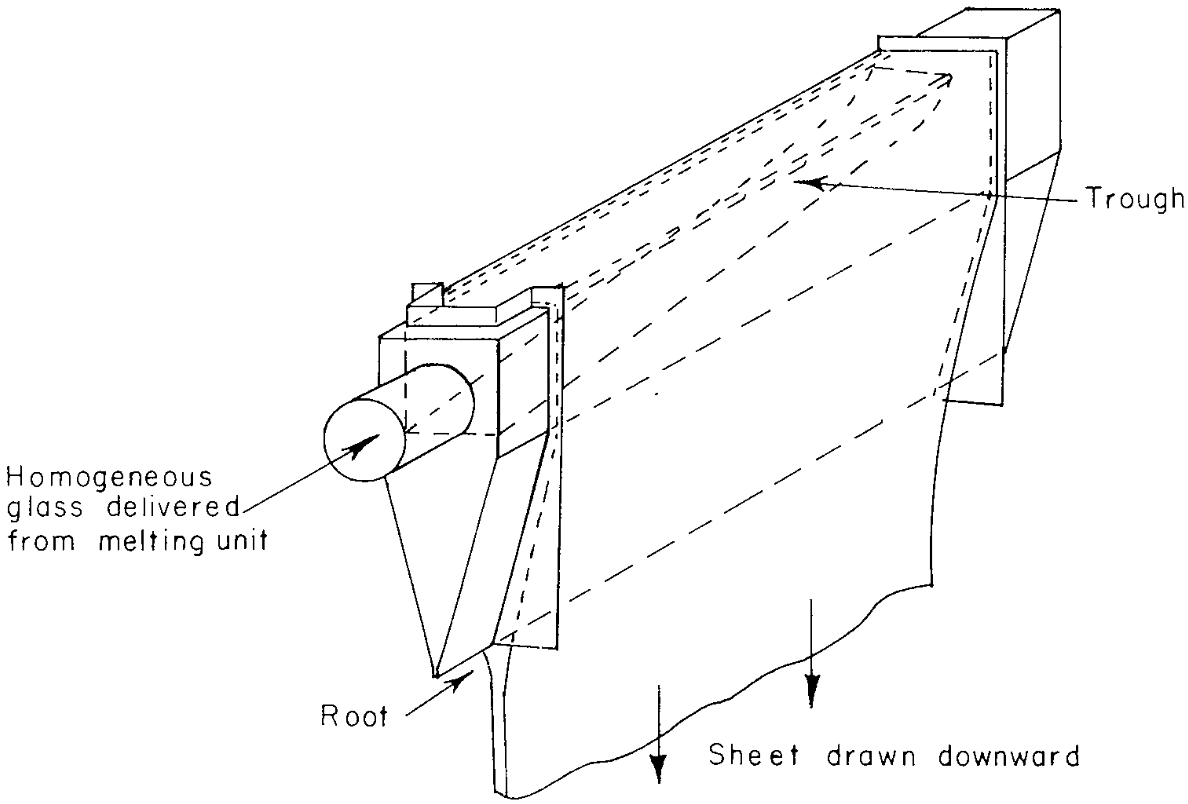


Figure 11--11. Fusion process.

Courtesy, Corning Glass Works

two streams rejoin or fuse together at the root or apex of the trough-like bar. The viscosity of the glass at this location is around 300,000 poises. Small metal rolls grip the edges of the sheet just below this apex to prevent excessive narrowing of the sheet as it is stretched. Further cooling as the sheet proceeds downward permits pulling rolls to be engaged on the sheet without causing any damage to the sheet surface. A vertical annealer with suitable pulling rolls conveys the glass ribbon to the cut-off station where it is cut to length.

Advantageous features of the process are:

(1) The glass surface is untouched by anything except on the sheet edges until it is sufficiently hard to resist marking. This yields a smooth fire-finished surface.

(2) The rate of glass flow is determined by the impedance of the delivery tubes and trough and is not in any way influenced by the speed of the pulling rolls. If the sheet breaks between the trough root and the first set of pulling rolls, the flow continues, and gravity conveniently supplies glass to the pulling rolls to restart the draw. This is particularly advantageous when drawing thin sheet. It also provides for unusual thermal stability in the glass melting furnace and the glass delivery system.

(3) Well stirred glass can be delivered to the trough by passing it through a narrow forehearth specifically designed for efficient glass mixing. This avoids striae and streak which can occur in thin float glass (0.090 inch thick).

(4) The process can be attached to a variety of glass melting and delivery systems that may be necessary for a particular glass. This, coupled with the fact that there is minimal contact and practically no chemical contamination of the soft sheet surface during forming, makes the process applicable to a wide range of glass compositions.

Corning Glass Works has produced fusion draw sheet from hard borosilicates

(Code 7740), even harder chemically strengthenable glass (Code 0311), and soft photochromic glasses for sunglasses (Code 8102). Sheet as thin as 0.025 inch and as thick at 0.460 inch has been produced on the process. Glass flow rates have varied from several hundred to several thousand pounds an hour. Usable sheet width is 60 inches after trimming off the edges, which represents an 18% loss.

13. Outlook

While the prediction of trends in the flat glass industry is a risky business at best, there are some directions in which progress over the next 10 years is fairly clear. One trend that will *not* continue, in the United States at least, is the replacement of plate and sheet glass by float; that phase is history. Indeed, with economists forecasting only modest growth in flat glass production during the 1980s[24], the emphasis for individual flat glass manufacturers will be on increasing market share, which translates at the production level to higher plant yields and lower unit costs. Emphasis will be on increased tank efficiency rather than increased throughputs, which was the trend through the early 1970s, until energy costs skyrocketed.

The technical advances in float bath technology will be in the direction of greater flexibility and automated process control, with design changes occurring slowly because of the relatively long service life of most bath components. Hopefully a breakthrough in materials suitable for use in the float bath environment will occur as well.

The various sheet processes are still being used worldwide and constitute approximately 75% of the world's flat glass manufacturing facilities. As the trend from the labor-intensive sheet processes to the more capital-intensive float processes begins to take effect on a global basis, active licensing activity should spread the technology of float forming even further.

As stated in the introduction, the 20th Century has seen two technological revolutions in flat glass manufacture. Is it possible that a third is about to occur, one which will replace the float glass process with another? While the possibility always exists, the prospects are unlikely, and it seems a good bet that float processes will continue to dominate the manufacture of flat glass well into the 21st Century.

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