An introduction to glass and glass fiber manufacturing technology with application to nonwoven process

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ABSTRACT: Glass making uses six to twelve individual ingredients. The paper discusses the source and function of each ingredient and details the composition and manufacture of glass fibers. These fibers find use in a variety of applications for nonwovens.

KEYWORDS: End use, equipment, glass fibers, nonwovens, processes, production, raw materials, utilization.

Brief history of glass making

The first evidence of glass making dates to 12,000 B.C. with the preparation of glazes. The oldest known pure glass is a molded amulet of deep lapis lazuli color found in Egypt which dates to about 7000 B.C. Glass making probably started in Assyria and Mesopotamia before moving to Egypt in about 1500 B.C. The Romans subsequently learned glass making from the Egyptians. Knowledge of the glass making craft passed to Rome and Venice, travelled slowly across Europe, and finally spanned the Atlantic to America.

History of glass fiber

People 3500 years ago used glass threads to make and decorate glass articles. From approximately 1500 B.C. to the first century B.C. people made glass vessels by winding coarse glass fibers onto a clay or sand mandrel which was suitably shaped. They heated the assembly until the glass fibers melted into each other. Then they carefully broke out the clay or sand former after cooling. Syrian, Roman, Italian, French, English, and German antique glass specimens show that glass fiber was wrapped around or gathered for outside decoration or even for article formation.

Glass fiberization

In the United States, ardent work on glass fibers began in 1931 in the laboratories of Owens–Illinois Co. and in 1935 at Corning Glass. In 1938, these two companies joined to form the Owens–Corning Fiberglas Corp. Games Slayter led the team performing the pioneering work then. The original laboratory setup consisted of an oxyacetylene burner into which they fed a glass rod. The combustion gases would draw molten glass from the end of the rod into filaments. Placing a wire screen in the path of the gaseous blast permitted the collection of fine fibers. This experiment was the first demonstration of drawing glass fibers with a technique other than direct mechanical pulley, i.e., by use of centrifugal force. This was the forerunner of the most widely used process in glass wool manufacturing.

A pilot plant for wool production used a trough shaped refractory container with holes drilled at 1.27-cm centers. Streams of glass emerged from these holes into an enveloping jet of high velocity steam. Because the refractory holes eroded rapidly, there was a change to a platinum metal alloy for the refractory liners. To obtain better control of glass stream temperatures, the use of platinum alloy later expanded to include application as an electrically heated resistance element. This was the beginning of the fiber forming component called "bushing." In bushing, the platinum alloy acts as the glass stream former, a furnace forehearth, or as an independent small melter. The team under Games Slayter soon developed a steam blowing process which now finds wide use for making continuous fiber for textiles or for reinforcement applications. From the time of this original work, there have been many advances in the processes for manufacturing basic wool and textile fibers.

Glass structure

Before one can become knowledgeable in glass fibers, it is necessary to have an understanding of the basic structure of glass and the factors which

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govern its properties both in bulk and in fiber form.

The American Society of Testing Materials (ASTM) defines glass as "an inorganic product of fusion which has been cooled to a rigid condition without crystallizing." Glass is a supercooled liquid whose structure has short-term order. It does not have long-term order like crystals. Ice is an example of a glass with a noncrystalline solid structure. Commercial glass fibers for nonwoven applications use silica which is a glass former. The basis of all silicate chemistry is the silicon–oxygen tetrahedron in which silicon is in a fourfold tetrahedral coordination with oxygen. This basic SiO_4 group has four oxygen atoms at the corners and a silicon atom at the center of the tetrahedron. Silica in all its forms exists as a polymer $(SiO_2)_n$. It does not have a melting point but gradually softens as the temperature increases to 2000°C. Heating silica until it is fluid and then cooling it forms a glass with random structure. Only prolonged heating above 1200°C (1100°C in the presence of impurities) will cause crystallization. This glass is quartz glass or fused silica. The drawbacks of the fused silica glass are the high melting temperatures which are necessary and the difficulty in processing it.

One prepares commercial glasses by melting and fusing a mixture of materials in temperature ranges of 1300–1500°C. In these glasses, the addition of other oxides modifies the silica network. These oxides fall into three groups:

- Other network formers such as boric oxide (B_2O_3) and alumina (Al_2O_3)
- Network modifiers compromising the alkalis (Na_2O, K_2O), alkaline earths (CaO, BaO), and most of the metals of the periodic table (Network modifiers cleave Si-O-Si bonds to reduce the temperature necessary for glass melting and forming.)
- Intermediate oxides (Al_2O_3, B_2O_3, MgO, PbO, BaO, MgO, TiO_2 and ZrO_2) which can function either as a network former or modifier depending on the composition and thermal history

I. Temperature range responses for viscosity of glass

Log η	Response
2.0	Melting and timing temperature
3.0–4.0	Forming and fiberizing range
3.0–7.0	Working range
7.65	Littleton softening point
13.0	Annealing point
14.5	Strain point

II. Requirements for fiber glass composition formulation and optimization

1. Properties and quality requirements of fibers for customer end use
2. Proper working characteristics for glass forming and fiberizing
3. Liquidus temperature
4. Adequate glass melting, time held at temperature, and homogenizing
5. Chemical durability and resistance
6. Product quality and quantity for optimum profitability from the total production system
7. Minimum corrosion on glass furnace refractory
8. The environment

This overly simplified description of the structure of glass provides an understanding of the properties of glasses in the glass fiber industry.

Raw materials for glass manufacture

Introduction

The raw materials for commercial glass making contain a mixture of six to twelve individual ingredients. A major portion of the batch comprises from four to six materials such as sand, soda ash, borax, boric acid, limestone, dolomite, feldspathic materials, etc. The remainder of the glass batch consists of several minor ingredients such as barium and zinc compounds, fluorides, sodium sulfate, carbon, etc. The major ingredients in the glass batch encompass three classes:

- Naturally occurring minerals which are mined or quarried such as sand, dolomite, feldspar, or limestone (Most of these require crushing, grinding, and bonification to remove unwanted impurities. The materials must meet certain physical and chemical specifications before use in the glass making.)
- Manufactured chemicals such as soda ash, borax, boric acid
- By-product materials such as cullet, slag from steel making, carbon, and sulfates

Raw material for silica

Silica or silicon dioxide (SiO_2) is the major component of most commercial glasses because it is the principal glass forming oxide. The main source is a quality sand of which large deposits of high purity occur in different parts of the United States. Glass making sands should normally pass a 20 mesh screen with the majority retained by a 100 mesh screen. The iron oxide content is normally below 0.03% by weight Fe_2O_3. For alkali free (E-glass) one grinds the sand and all batch materials to minus 350 mesh. The Fe_2O_3 content can be as high as 0.1% by weight.

Raw material for sodium oxide

Sodium carbonate and soda ash (Na_2CO_3) are the main sources of sodium oxide or soda in the glass batch. Soda ash comes from the mineral trona, which occurs naturally in Wyoming. The sodium carbonate comes from dissolution of the mined material, separation of impurities by filtration, crystallization, and calcination. Europeans use Solvay process soda ash from treatment of a sodium chloride brine with ammonia and carbon dioxide under pressure to form sodium bicarbonate. After calcining, the bicarbonate forms the carbonate.

Raw material for alumina

Feldspar is one of the major sources of

III. Typical fiber glass compositions

Oxide	Rotary (insulation)	E-glass	Evanite M-glass (C-type)	Evanite B-glass	Schuller 753 (C-type)	Schuller 475 glass	363 (Aerocor)
SiO_2	60–65	54–55	62–69	57–65	62–65	57–58	58–59
Al_2O_3	3–7	14–15	3–6	5–7	3–5	5–6	5
B_2O_3	4–9	7–8	4–6	8–11	5–6	10–11	7–8
CaO	4–10	18–21	5–6	2–4	5–6	2–3	0–2
MgO	0–4	0.3–3	2–4	0–2	2–3	0–0.5	
BaO	0–0.2		0–0.02	2.5–5.5	0–0.02	5	
ZnO				2–4		4	
Na_2O	15–17	0–<2	11–16	8–11	14–16	10–11	14–15
K_2O	0–2	0–0.4	0–3	2–3.5	0–1	2–3	
ZrO_2							4
TiO_2		0.5–0.6		0–0.1	0–0.1	0–0.1	8
F_2		0–1	0–1	0–1	0–1	0–1	0–2

IV. Physical properties of fiber glasses

Properties	Rotary (insulation)	E-glass	M/753 family (C-type)	B/475 family	363 (Aerocor)
Tensile strength, 21°C, 10^6 psi					
A. Virgin fiber	350	500			
B. Commercial grade	120–200	370			
Density	2.54	2.60	2.50	2.55	
Softening point, °C	675	845	675–700	675–695	
Service temp., °C	480	540	480	480	480
Durability, weight loss, %	2.1	0.7	1–1.8	1–1.2	1.1
Refractive index	1.51	1.55	1.51	1.53	1.55

alumina in glass. The chemical formula for feldspar is $R_2O{\cdot}Al_2O_3{\cdot}6SiO_2$ where R_2O is an alkali oxide such as Na_2O or K_2O. Low iron, glass grade feldspars with 18–19% by weight Al_2O_3 occur in North Carolina. Nepheline syenite with alumina contents from 22–26% by weight occurs in Canada. The mesh size of feldspars for glass making is –30 to +40. One uses kaolin ($Al_2O_3{\cdot}2H_2O$) or clay of low alkali content for E-glass. It is a fine powder which is mostly minus 350 mesh particle size containing 36–39% clay, a maximum of 2% Na_2O and K_2O, and 1% Fe_2O_3 by weight. Synthetic alumina hydrate ($Al_2H_3{\cdot}3H_2O$) or the calcined form is a substitute when there is no suitable feldspar or clay.

Raw materials for calcium oxide and magnesium oxide

Calcium oxide derives from calcium carbonate which is either precipitated chalk or natural limestone. Natural limestone is available in varying degrees of purity with CaO content of 54% to slightly less than 56%.

Dolomite is an equimolecular mixture of magnesium and calcium carbonate or 30% CaO and 20% MgO on a weight basis. Sometimes one uses burnt dolomitic limestone for glass making. In the United States, calcitic and dolomitic limestone occur in Ohio, Pennsylvania, Missouri, New York, Kentucky, Texas, Utah, and California. Using fluorspar which contains 70% CaO by weight also provides a source of calcium oxide in the batch.

Raw materials for boric oxide

Most of the boric oxide in glass comes from sodium borate ($Na_2O{\cdot}2B_2O_3$) in the mineral borax, which occurs in California. Colemanite is a calcium borate mineral which finds direct use in E-glass. One may also convert it to boric acid. The preferred form for a sodium borate addition to the glass batch in the United States is the borax with five molecules of hydrated water ($Na_2O{\cdot}2B_2O_3{\cdot}5H_2O$).

Raw materials for fluorine

Fluorine (F_2) is an additive in glass making at a level of less than 1.0% by weight which reduces glass viscosity. Calcium fluoride (CaF_2) occurs in fluorspar, a naturally occurring mineral. Other sources for fluorine are sodium silicofluoride (Na_2SiF_6), which is a synthetic compound, and the complex sodium aluminofluoride (Na_3AlF_5) or cryolite.

Raw material for barium oxide

Barium carbonate from the purification of the natural mineral, witherite, is the preferable source. Sometimes one uses barium sulfate or the natural mineral, barytle, in glass making to give a barium oxide content in the glass of about 0.5% by weight. Barium sulfate also acts as a refining agent.

Raw material for zinc oxide

One introduces zinc oxide (ZnO) into glass as the oxide itself. The oxide comes from the direct oxidation of the metal and subsequent purification by sublimation. A small amount of zinc oxide in glass imparts water resistance. Because of its high cost and a tendency to increase crystallization, it finds limited use in glass.

Use of salt cake or sodium sulfate

(Na_2SO_4) is a source of soda in glass. It is a by-product in the manufacture of hydrochloric acid made from sodium chloride and sulfuric acid. The use of sulfate in the glass batch from 0.1–0.3% by weight of SO_3 increases the melting

rate of the batch and improves glass homogeneity and refining. In the presence of carbon, the sulfate reduces to sulfide which has a better reaction during melting of the glass batch. It dissolves residual sand grains, reduces silica, and refines the melted glass.

Use of gypsum

Gypsum, anhydrite, or dead-burnt gypsum ($CaSO_4$) sometimes substitute for salt cake in glass melting, particularly for E-glass.

Use of carbon

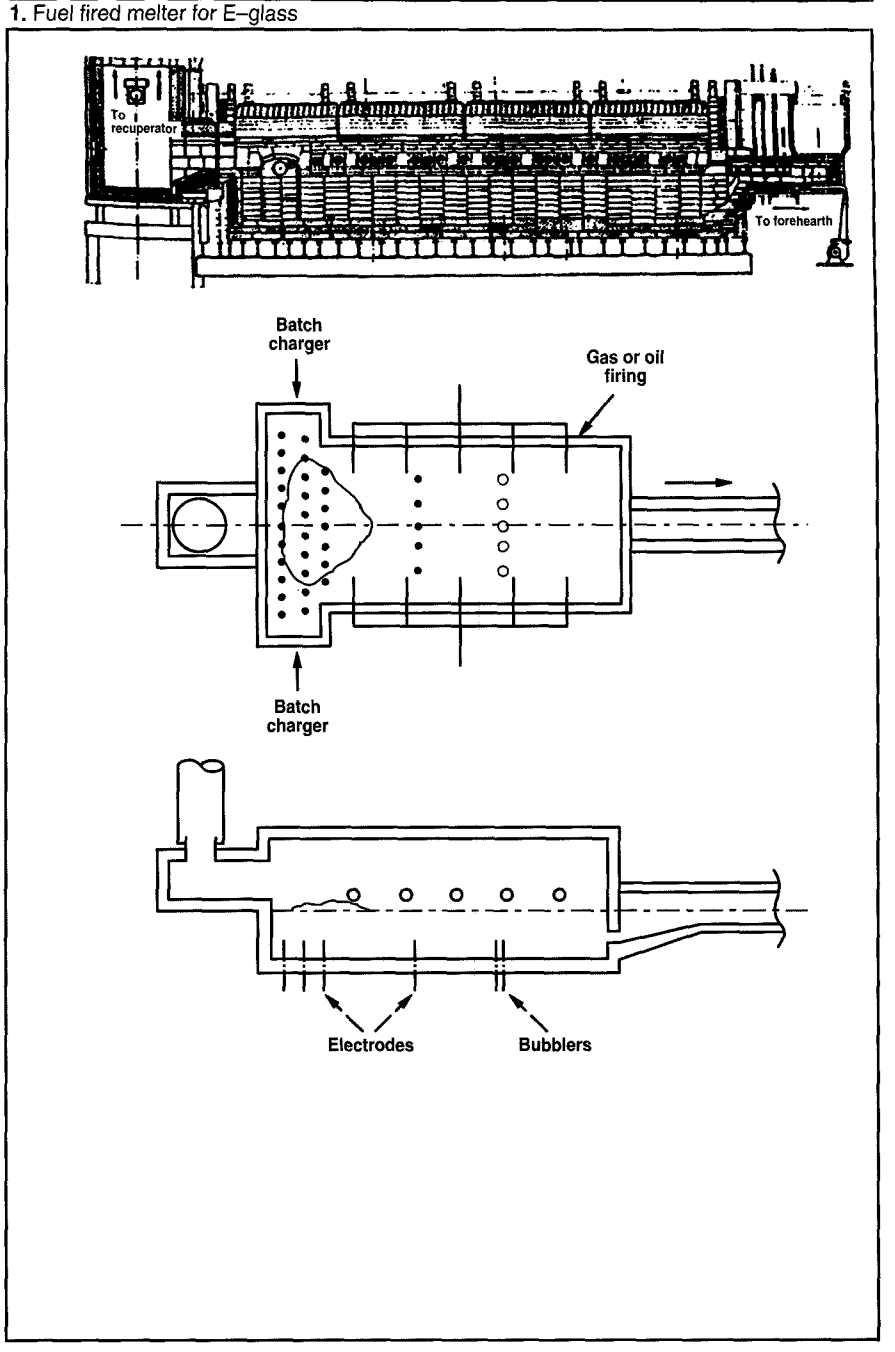
Carbon is a reducing agent which produces sulfide from sulfate. Anthracite coal and petroleum coke are the forms for addition of carbon.

Handling of raw materials

The glass batch is a mixture of the weighed materials carefully blended to give homogeneous glass of the intended composition. This is a very important operation. For good production of glass, the following points need detailed attention and care:

- All raw materials in the glass plant require receipt, storage, and handling so they have known compositions before use. It is also necessary to avoid segregation by particle size.
- Each supplier must ship material within the required specifications and provide a certificate of analysis with each delivery. Samples taken before unloading ensure that the material will conform to the specifications.
- All batch weights must be accurate and precise to ensure that the glass composition and properties remain within acceptable limits.
- The handling of raw materials and batch should not release dust into the atmosphere.
- Storing, conveying, and addition of the mixed batch must occur in a way that there is no segregation of raw materials.

1. Fuel fired melter for E-glass



Glass compositions

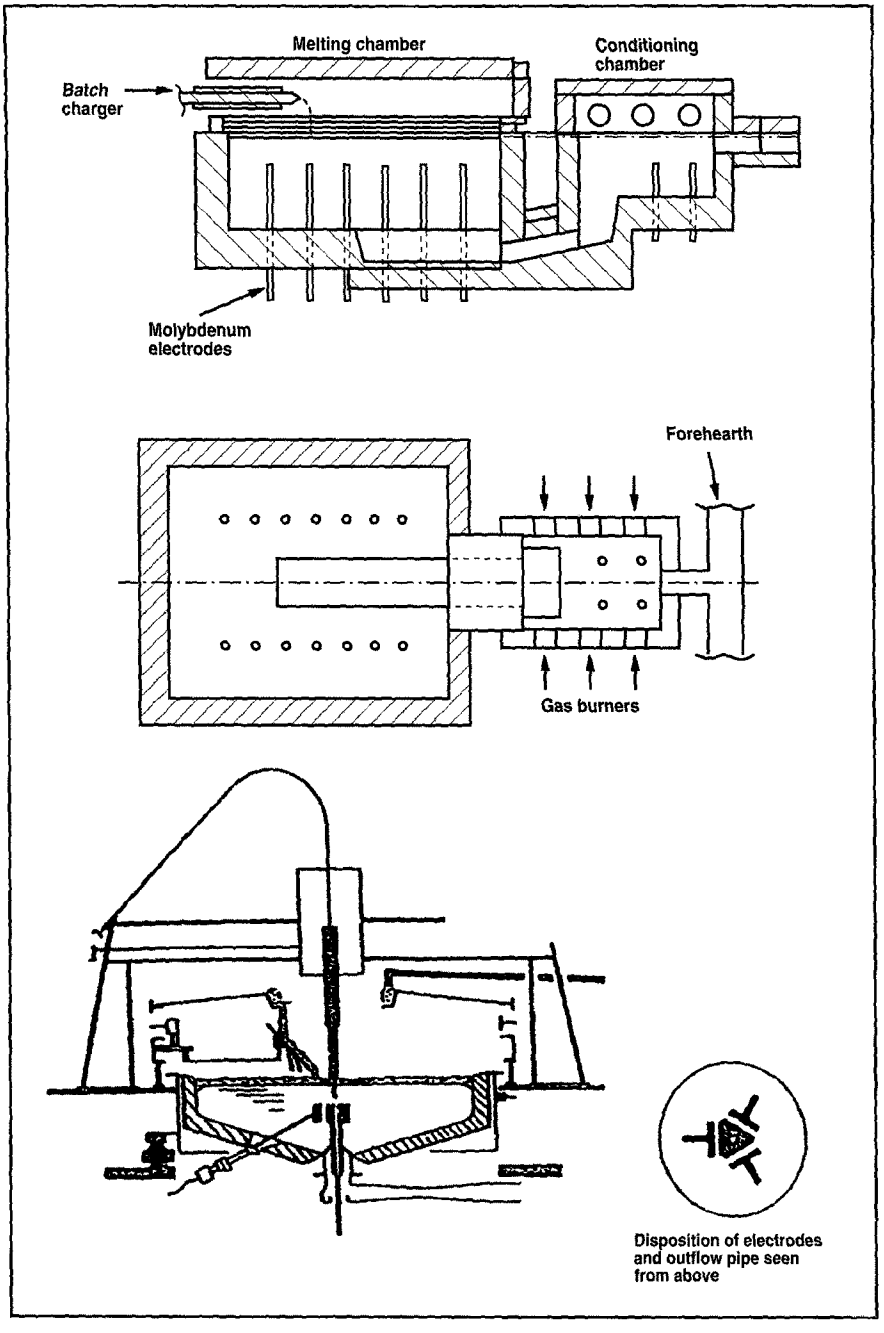
General

During glass melting and processing, the working characteristics of a glass depend very much upon chemical composition. This is the principal influence on the viscosity relationship with temperature. **Table I** shows the important points on the glass viscosity curve with the corresponding responses.

The magnitude of viscosity at the beginning of glass forming is about 3 ($\log \eta = 3$). For most glass fiberization the viscosity is in the range between 3 and 4. There is a limit to glass flow when $\log \eta$ is about 7. In the working range the viscosity of glass doubles for each 5.5°C lowering of temperature.

Glass composition formulation requires a detailed knowledge of the viscosity curve. Liquidus temperatures

2. Electric melter



and phase diagrams of glasses are also very important considerations. The liquidus temperature for a glass composition is the temperature below which crystallization of the glass will occur, if there is sufficient time. Above this temperature all crystals will completely dissolve. The glass fiberizing temperature should be well above its liquidus temperature so that devitrification and crystallization do not occur leading to manufacturing problems. Only a very small amount of crystalline particles will require scrapping the glass. **Table II** lists factors which are important requirements for fiber glass composition formulation and optimization.

Fiber glass compositions

Table III, which shows typical fiberglass compositions, and **Table IV**, which shows physical properties of fiber glasses, indicate the various types of glasses for commercial fiber manufacturing. The major portion of glass fiber is either rotary wool glass (AF) or E-glass.

Rotary wool glass is a family of soft alkali borosilicate glasses with improved durability over alkali lime sheet and bottle glasses (A-glass) from which they derive. One produces these fibers by using the rotary wool processes used for thermal and acoustic insulation.

E-glass is a calcium aluminoborosilicate with boric acid and less than 2.0% alkali. Most of the continuous filament glass fibers today consist of E-glass composition. Originally developed for electrical applications, this is now a general purpose glass for reinforcement applications. Only a small portion finds use for electrical applications.

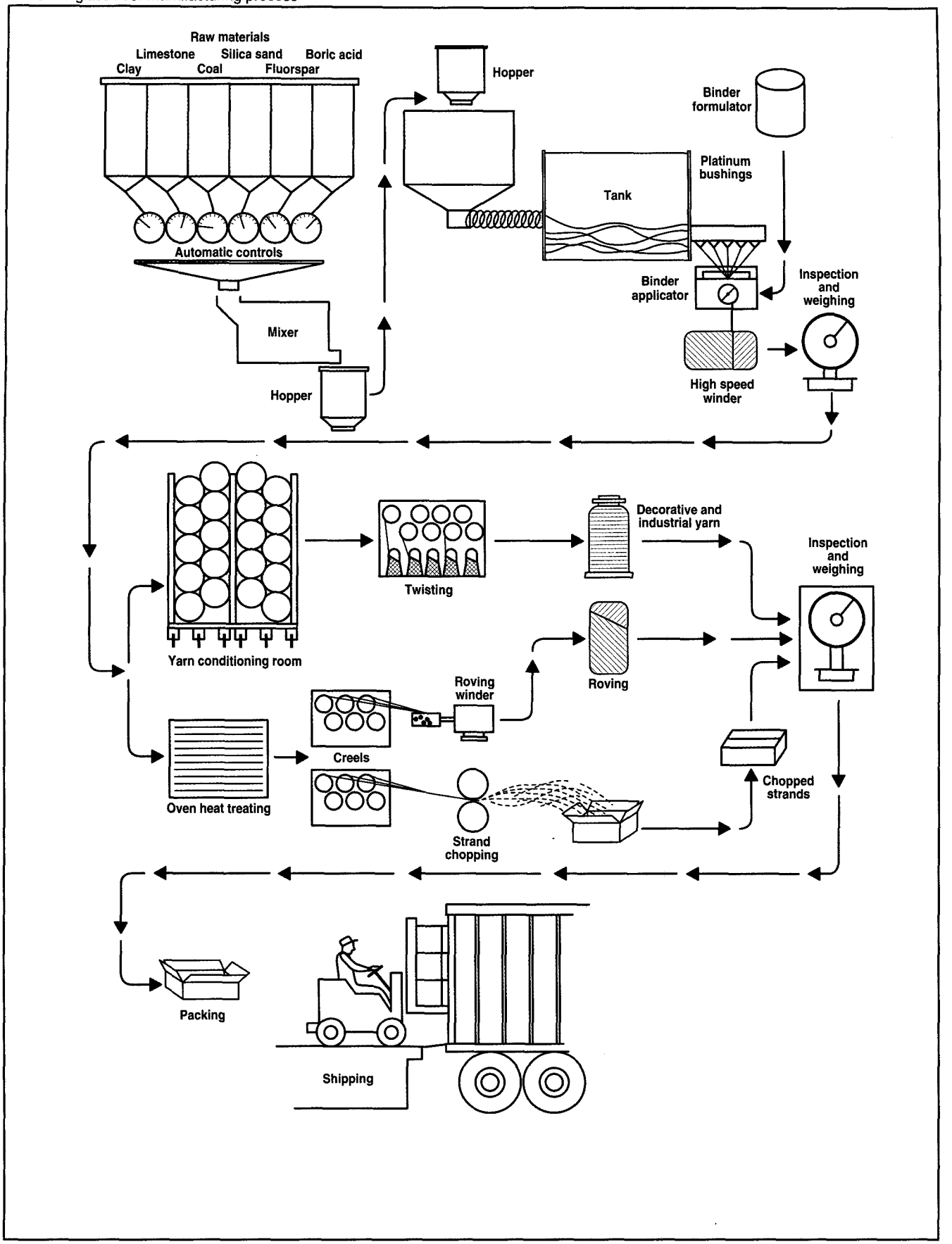
Other commercial compositions

There are applications for glass fiber which require special formulations for specific diameter distributions.

C-glass is a soda lime borosilicate composition whose initial use was for chemical resistance to acids. C-glass finds use in filters (wool) and composites (continuous filament, reinforcements) which will contact acids, since dilute mineral acids attack E-glass. C-glass is easier and cheaper to manufacture than E-glass and therefore finds successful use as a reinforcement of bituminous roofing sheets. A special C-glass composition is useful for making fine diameter wool fibers from 0.75 to 3 μ for battery separator media (paper). The purpose of the media is to separate the positive and negative plates within the lead acid battery. Evanite's M-glass composition and Schuller's 253 and 753 are special C-glasses.

The B-glass and 475 glass are special wool glass formulations for the production of fine fibers 4–0.1 μ in diameter with a specific fiber diameter distribution for nonwoven media application. Air and liquid filtration and aircraft insulation use glass micro-fiber media, because these fibers

3. Textile glass fiber manufacturing process



have good resistance to humidity and weather.

363 (Aerocor) is a special glass containing high TiO_2 and ZrO_2 for fine fiber applications requiring good weather resistance.

Furnaces for glass fiber production

There are two basic categories of furnaces for melting the glass. **Figure 1** depicts the fuel fired melter sometimes knows as a unit melter. This is the common furnace for glass melting without recuperative heat recovery. Development of these small continuous tank furnaces occurred in the 1940s for the container glass industry. This design contains a rectangular melting chamber with a high length-to-width ratio of about 3:1 and a low depth of 60–100 cm. It fires by use of opposing gas flames across the width of the furnace. The combustion air preheats by passing through cylindrical nickel chromium alloy recuperators (heat exchangers). Molybdenum rod electrodes from the bottom on occasion provide electric boosting, particularly for E-type glasses.

The second type of furnace for the fiber glass industry is the totally electric melter as shown in **Fig. 2**. This type of melting is very useful with fluoride, boron, and lead containing glasses. When a flame sweeps across such glasses in a fuel fired furnace, considerable amounts of the volatiles depart with the flue gases. To meet air pollution regulations, appropriate pollution control devices must treat these volatiles in the flue gases. This can be quite expensive to operate and require high capital expenditures. In electric melting, heat generates below the batch blanket which melts and dissolves the glass from underneath. The blanket of cold batch on the surface of the melt prevents heat loss from the molten glass and acts as a zone where the volatile oxides can condense. The investment cost per ton of glass is considerably lower for the totally electric furnace compared to the gas fired unit melter with alloy recuperators and pollution control devices. With the newer oxy-gas melters without a heat recovery system, investment costs are slightly lower than conventional unit melters. With electric melters, however, operating costs are higher than fuel fired furnaces. There are no costs for pollution control devices.

The refractory used for furnace construction depends upon the type of glass undergoing melting and the type of furnace which is in use. For E-glass, sintered chrome products find greatest use. For soft alkali borosilicate glasses, fused alumina zirconia silica (AZS) refractory with 41% ZrO_2 is useful where the melted glass has a low limit for Cr_2O_3 content. Otherwise, there is a fused chrome (Cr_2O_3) and alumina (Al_2O_3) refractory for melting fiber glasses to give longer furnace life.

The de Bussy/Pochet Furnace is a French design electric unit for melting fiber glasses, alkali borosilicate, insulation wool, and E-glass with little or no alkali. A round, water cooled copper shell in the shape of a bowl has an inside refractory lining 10–23 cm thick which acts as a radiation shield. The glass in contact with the cooled refractory has high viscosity. Figure 2 shows a cross sectional view of the round electric melter. Refractory wear is high due to the very high glass temperature and convection currents. Alternating current heats three molybdenum electrodes which encircle the glass discharge pipe which is electrically neutral.

Glass fiberization

Figure 3 depicts a textile fiber forming process with continuous filaments. Glass from the melter goes directly to platinum bushings through a forehearth which could be 9–21 meters long. Because of the iron content, the glass depth in a gas fired forehearth is about 10 cm in the conditioning (cooling) section and about 6 cm in the sections where bushings operate. The molten glass flows into an electrically heated (resistance) platinum and rhodium bushing in rectangular shape with 400–4000 cylindrical nozzles at its base. The glass coming out of the nozzles is mechanically drawn or attenuated into fibers from 4–20 μ in diameter at speeds in excess of 1.5 km/min. After application of a protective organic sizing, the filaments gather into one strand or into a number of substrands which then wind onto a rotating cullet to form the cake. Next there is either precision chopping into lengths for reinforcement or nonwovens applications or processing into a continuous yarn for weaving.

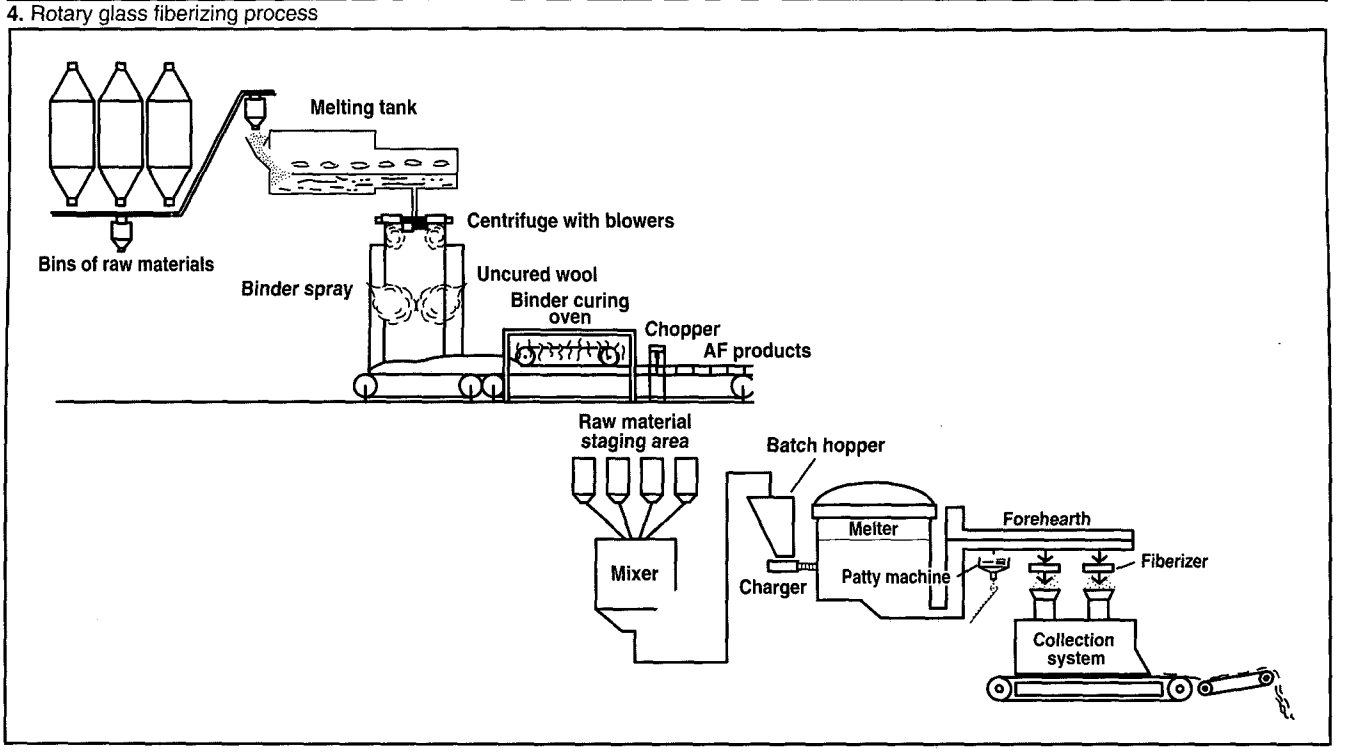
Instead of making fibers directly from molten glass, some companies use marbles or rods remelted in platinum alloy bushings similar to those described previously.

Wool forming process

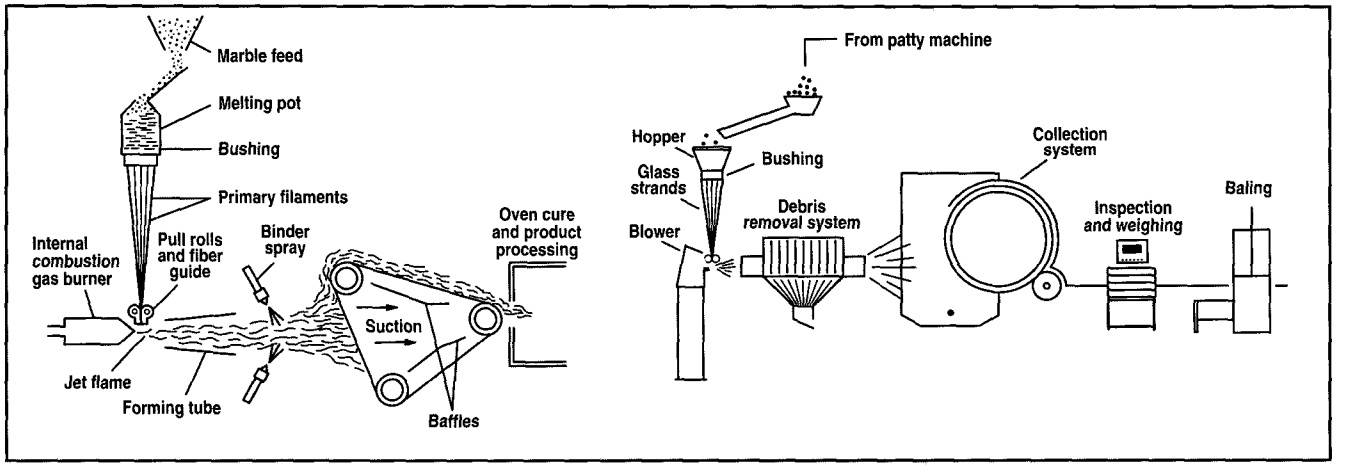
Figure 4 shows the process of making rotary wool fibers in a process similar to a cotton candy machine. Molten glass falls into a hollow rotating cylinder. This is a "spinner." It has many holes in its vertical sidewall edge. Centrifugal force of the rotating spinner forces the glass to extrude laterally out of the numerous perforations. A high velocity hot glass blower further attenuates the centrifuged fibers by maintaining the viscosity at a low enough level. Fibers from the rotary process are discontinuous with a typical diameter range of 0.5–7 μ. Rotary fibers tend to have a wider diameter distribution. Fibers blown onto a metal line conveyer belt collect under a slight vacuum. There is a spray of binder materials before collection to establish mat integrity for some applications.

Figure 5 shows preparation of flame attenuated super fine wool fibers from molten glass either directly from a furnace or by the remelting of marbles. Primary filaments of 0.0025–0.0038 cm in diameter first draw from the base of a multi-holed bushing. These coarse filaments pass through rollers and fiber guides into a high velocity jet of gas and air flame. The primary filaments melt and then attenuate (thin and lengthen) by the high kinetic energy of the gas stream. By controlling the primary filament di-

4. Rotary glass fiberizing process



5. Flame attenuation process



ameter, the velocity of the pull rolls, and the temperature and velocity of the gas and air jet stream, it is possible to obtain a consistent average fiber diameter.

Controlled attenuation technology (CAT) shown in **Fig. 6** is a process which produces fibers by feeding glass into a rapidly rotating centrifugal bushing with a perforated circumference. In this case, the bushing has fewer holes than the typical rotary process and the flow per primary filament is about four times greater and has a fiberizing jet of much higher velocity than the rotary process. The combination of high jet velocity and unrestricted ambient air on both sides of the fiberizing zone is similar to the flame blown process.

Application of special glass fibers for nonwovens

There are generally two types of glass fibers for nonwovens applications in the paper industry.

Chopped strand is continuous filament glass fibers composed mostly of E-glass with surface coatings and diameters from 5–16 μ. Their length after chopping is about 0.6–2.5 cm. These fibers provide tensile strength in nonwovens media.

Special purpose glass fibers are discontinuous glass fibers (wool) without any surface treatment having diameters in the range of 0.1–5 μ. Their use is for special filtration requirements such as air or liquid separation as well

V. Industry available special purpose fibers with average diameter

Average fiber diam., μm [a]	*Evanite glass*	*Evanite code*	*Schuller glass*	*Schuller code*
0.26			90	475
0.32	700	B	100	475
0.40	702	B	102	475, 753 [b]
0.50	704	B	104	475, 753, E
0.60	706	B, M		
0.65			106	475, 753, E
0.75			206	475, 753
0.80	708	B		
1.00			108A	475, 753
1.60	509	B		
1.80			108B	475, 753, E
2.30	510	B		
2.50	410	M		
2.60	610, 710	M, B		
2.70			110	475, 753
2.90			BX	475, 753
3.00	411	M	210	475, 753
3.70	612	M		
3.90	712	M, B		
4.00			112	475
4.10			212	475
4.30	413	M		
5.20	716	M, B		
5.50			CX	475, 753
6.10	717	M, B		
8.50	719	M, B		

[a] The intended mean diameter based on Bruneau, Emmel, and Teller (BET) surface area measurements. Microscopy values do not differ greatly.
[b] 253 is the designation for the most recent formulation in the 753 family.

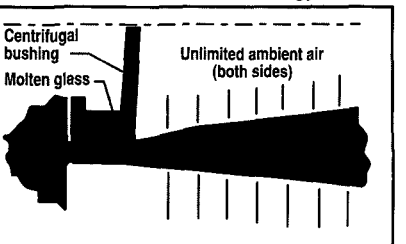
VI. Special purpose wool glass fibers

"HEPA" or absolute air filtration media
"ASHRAE" or medium to high efficiency air filtration media
Industrial respirator media
Air, fluid, or mist filtration and separation cartridge media
Low efficiency, commodity air filtration media
High efficiency thermal insulation
High efficiency acoustical insulation
Conventional "leaf" type battery separator
Absorptive recombinant battery separator
Asbestos replacement applications requiring fine fiber diameter and high temperature resistance
Chemical pipe and vessel construction media
Electrical grades
Organic pulp enhancement
Chopped strand replacement
Cryogenic insulation
Fiber reinforced plastics
Thixotropic additive

VII. Letter codes for special purpose fibers

Naval Research Laboratory code	*Mean fiber diameter, μm*
B	2.6–3.8
A	1.6–2.6
AA	0.75–1.6
AAA	0.5–0.75
AAAA	0.2–0.5

6. Controlled attenuation technology



as for special thermal or acoustic insulation in aircraft, aerospace, and cryogenic applications. These wool fibers have short, random lengths which intertwine. They have a length to diameter ratio ranging from 500:1 to 4000:1. Glass wool fibers are also available with diameters from 5-13 μ.

Traditionally, the majority of very fine diameter glass fiber wool found use in papermaking for the production of high and medium efficiency filtration media. Because of their unique properties, there is now a wider range of product applications for fine diameter glass fiber wool as shown in **Table V**.

Table VI shows the industry available grades of special purpose wool glass fibers differentiated by average fiber diameter and glass composition. **Table VII** provides the Naval Research Laboratory letter codes for special purpose fibers.

Conclusion

Glass making has existed for over 12 centuries, and glass fibers date to 1500 B.C. This paper has reviewed the functions of the various ingredients used to make glass and has summarized the aspects of fiber glass composition and manufacture.

Although the technology for glass fibers is extremely old, there are a multitude of modern applications. These include filtration, insulation, mechanical, and similar uses. ◼

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