MIL-HDBK-722(MR)
1 AUGUST 1969

MILITARY STANDARDIZATION HANDBOOK

GLASS

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DEPARTMENT OF DEFENSE
WASHINGTON, D. C.

MIL-HDBK-722(MR)
Glass
1 August 1969

1. This standardization handbook was developed for the Department of Defense in accordance with established procedure.

2. This publication was approved on 1 August 1969 for printing and inclusion in the military standardization handbook series.

3. This handbook provides basic fundamental information on glass products for the guidance of engineers and designers of military materiel. The handbook is not intended to be referenced in purchase specifications except for informational purposes, nor shall it supersede any specification requirements.

4. Every effort has been made to reflect the latest information on glass products. It is the intent to review this document periodically to insure its completeness and currency. Users of this document are encouraged to report any errors discovered and recommendations for changes or inclusions to the Director, Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172, ATTN: AMXMR-QS.

Preface

This is one of a group of handbooks covering materials used in the design and construction of military equipment.

The purpose of the handbook is to provide technical information and data about glass products for use in achieving the objectives of the Defense Standardization Program. The handbook is intended for use, as applicable, in engineering design, development, inspection, procurement, maintenance, supply, and disposal of equipment and materials. Whenever practicable, the various types, classes, and grades of materials are identified with applicable government specifications. Corresponding technical society specifications and commercial designations are listed for reference.

The numerical values for properties listed in this handbook are in agreement with values listed in the issues of specification in effect on the issue date of the handbook. The handbook values may, in some instances, differ from those listed in current specifications because of revisions or amendments made to specifications after publication of the handbook. In connection with procurement, it should be understood that the issue of specifications listed in the contract govern requirements.

Whenever specifications are referred to in this handbook, only the basic designation is given; all revision and amendment symbols are omitted. This is done for simplification and also to avoid the necessity of correcting the handbook whenever specifications are revised or amended. Current issues of specifications should be determined by consulting the latest issue of the "Department of Defense Index of Specifications and Standards."

The handbook was prepared by Mr. Errol B. Shand, Technical Consultant on the use of Glass and Ceramic Materials, Corning, N.Y., the John I. Thompson Co., Washington, D.C., and the Army Materials and Mechanics Research Center, Watertown, Mass. Comments on the handbook are invited and should be addressed to:

The Director
Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172
ATTN: AMXMR-QS

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Acknowledgments

The list of references in Appendix B of this manual represents only a small part of the author's indebtedness to the work of others in this field. Specific acknowledgements are made as follows:

Academic Press Inc., New York, (Reference [7]), Figures 1 and 2, slightly modified; Figures 8, 9, 19, and 30.

American Ceramic Society, Columbus, Ohio; Journal, Figures 6 and 27: Bulletin, Figure 25.

American Society for Testing Materials, Philadelphia, Pa., ASTM Desig. C-162; many definitions in the glossary.

Corning Glass Works, Corning, N.Y., Figures 3 and 13; also much of the data used for Figures 11, 15, and 16.

Glass Industry (The), New York; (Reference [30]), Figures 28 and 29.

Glastechnische Berichte, Frankfurt (Main), Federal Republic of Germany; (Reference [12]), Figure 3.

McGraw-Hill Book Company, Inc., New York (Reference [6]), Figures 17 and 18; some of the data on properties, such as in Table V, VI, and VII, are summaries obtained from this book.

Pilkington Brothers, Ltd., St. Helens, England (Reference [32]), Figure 18.

Wright Air Development Center, Wright-Patterson Air Force Base, Ohio; (Reference [26]), Figure 22.

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Chapter 1

Introduction

PURPOSE

MIL-HDBK-722(MR) was developed for the Department of Defense (DOD) in accordance with standard procedure and in compliance with policies and requirements of the Defense Standardization Program (DSP).

DOD Directive 4120.3 establishes and, together with Defense Standardization Manual 4120.3-M, "Standardization Policies, Procedures and Instructions," implements the DSP. Because of the comprehensive description of the DSP provided in these documents a detailed discussion is not presented here. However, the following definition of standardization, taken from DOD Directive 4120.3, in effect summarizes the DSP.

"Standardization is the adoption and use (by consensus or decision) of engineering criteria to achieve the objectives of the DSP. These criteria are applied, as appropriate, in design, development, procurement, production, inspection, supply, maintenance and disposal of equipment and supplies."

As implied in the preceding definition, the mission of the DOD with respect to standardization is to develop, establish, and maintain a comprehensive and integrated system of technical documentation in support of design, development, engineering, procurement, inspection, maintenance, and supply management.

MIL-HDBK-722(MR) is one of a group of standardization handbooks covering materials used in the construction of military equipment. These handbooks are part of the previously referenced integrated system of technical documentation developed, established, and maintained by the DOD in support of the DSP.

The basis for the development of MIL-HDBK-722(MR), then, is the DSP. The specific purpose of MIL-HDBK-722(MR) is to provide technical information and data on glass products for use in achieving the objectives of the DSP. The provisions of DOD Directive 4120.3 apply to all departments and agencies of the DOD, consequently, the data provided by the handbook are intended for application, as appropriate, in design, development, procurement, production, inspection, maintenance, supply, and disposal of military equipment and supplies.

SCOPE

1. **General.** MIL-HDBK-722(MR) contains technical information and data pertaining to products formed from glass.

2. **Definitions.** As considered here glass is an inorganic noncrystalline material (defined in more detail in the beginning of Chapter 2). Glass which is melted and formed and then transformed to a crystalline body, sometimes called glass-ceramic, is also considered briefly. Neither industry nor any organization has identified compositions and properties of commercial glasses except in a general way, and no glass specifications have been established for this purpose. Compositions of a number of commercial glasses listed in Table 1 are merely representative of the indicated types. Glass designations of individual glass makers may represent specific compositions, but these have been avoided here. Many glass compositions have been and are being developed for special applications. Except for several types of particular interest for military purposes they are not considered here.

3. **Contents.** It is anticipated that this handbook will be used by personnel engaged in any of a variety of occupations including engineering design, development, procurement, inspection, manufacturing, supply, maintenance, and disposal of military equipment and materials. To satisfy

the wide range of this audience the discussion of glass products ranges from the preparation of raw materials to the forming and finishing of the final products.

Tables are included to indicate representative values of the physical properties of some common commercial glasses, but minimum values of these properties, as are sometimes used as application data for other materials, are not given. Because of the brittle nature of glass the number of significant mechanical properties which can be listed is limited. Furthermore, breaking stresses are not explicitly correlated with composition or type, but rather on methods of forming and treatment. Consequently strength data cannot be tabulated for glasses.

a. Chapter 1. Chapter 1 is a short introductory chapter in which the purpose and scope of the handbook are identified, and a brief review of glass product development and use is presented.

b. Chapter 2. This chapter describes how certain chemical compositions can be cooled from the molten state to form the characteristic structure of the glassy state. It is noted that some unusual properties are associated with this structure. Common glass-forming constituents are noted and examples are given of compositions of a few common glasses. Melting operations are described briefly, as are the common methods used for forming various kinds of products while the glass is still in its viscous condition. Some of the many types of finishing operations which are carried out on the glass after its original forming are mentioned.

c. Chapter 3. This chapter on selection criteria for glass is concerned primarily with its properties. Certain properties, such as viscosity and brittleness, are peculiar to this material so that their treatment has been relatively expanded. The wide use of glass for the transmission of light requires the consideration of its optical properties. All property values given here must be accepted as approximate because compositions of the various types are not definitely fixed.

d. Chapter 4. Chapter 4 includes discussions of several technical matters not considered elsewhere. There is a brief analysis of the thermal

treatments of annealing and tempering. Procedures for strength testing are included because types of tests commonly applied to other materials are not readily adaptable to brittle materials. In addition to the conventional methods of determining breaking stresses, the subject of *fracture analysis of glass is discussed.* One unusual feature is that breaking stresses can usually be estimated from markings on the fracture surface with a fair degree of accuracy. The use of this method is particularly useful in the diagnosis of fractures which occur in service.

The structural design of brittle materials imposes limitations which may be of little importance for materials of a more conventional kind. Not only are the characteristics of mechanical failure different for glass, but the results of failure can be catastrophic. Although design principles are similar to those for other materials, the general philosophy of design and the direction of approach will be modified. Actual design procedures used constitute much more than the substitution of properties, including an assumed breaking stress, than in the procedures used for metals. These distinctions are discussed briefly.

e. Chapter 5. This chapter discusses some representative applications of glass which are of military significance. The discussion attempts to show the engineering principles involved in *the various designs rather than structural details.* Many of the military uses of glass involve the transmission of light for purposes of glazing and vision through the medium. Such glazing components in widely different fields have been considered. It is shown that when requirements become more varied and more severe, both the type of glass and the structural design of components may be modified greatly.

It is noted that glasses may be required to transmit or absorb radiations in parts of the electromagnetic spectrum beyond the visible range. Glasses of special properties are often used for such purposes. Plastics reinforced with glass fibers may be used to overcome some of the mechanical limitations of massive glass components. This composite material is shown to have many applications.

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f. Chapter 6. This chapter deals with the subject of quality assurance. No single means, taken alone, will provide this assurance. The first requisite lies in the ability of the supplier to provide glass material and products which will function satisfactorily in service. Then there should be some criterion embodied in a product specification for verifying the suitability of the product at the time of acceptance. Requirements to be met by the product and test procedures for verification of compliance are both included in such specifications. It is possible for products to meet the requirements of a specification and still not operate satisfactorily in service. This can occur if the requirements and tests of the specification are not related properly to conditions which will be encountered in service. As a consequence, a product specification is subject to review and change. This can result from changes in service conditions or from some development of the product which may affect its performance. These factors should be kept in mind when any specification is being considered.

This chapter lists a number of federal and military specifications related to glass products. These specifications are for products of massive glass, although some are for composite materials.

Many other specifications have been issued in special fields, including electronic tubes and components, fibrous glass, and glass reinforced plastics.

USE OF HANDBOOK

4. Objectives. This handbook is intended to be used in achieving the objectives of the Defense Standardization Program, established in DOD Directive 4120.3. Essentially, it serves as a means of disseminating technical data and information about glass products to cognizant and interested personnel of the Department of Defense and associated government and industrial organizations. The use of the handbook in fields of interest such as design and development engineering, procurement, inspection, manufacturing, maintenance, and supply of military equipment and materials certainly does not require explanation or elaboration. The limitations of the handbook, however are indicated in the following paragraph.

5. Limitations. This handbook, although it contains lists of military as well as nongovernmental specifications and standards, and data relative to them, is of course not a specification or a standard. Thus the handbook should not be referred to in purchase orders or in contracts.

Chapter 2
Glass Technology

STRUCTURE

The American Society for Testing and Materials defines glass as "an inorganic product of fusion which has cooled to a rigid condition without crystallizing." This definition, which is accepted in the discussion, places glasses within the broad classification of ceramic bodies, but distinguishes them from other ceramics because of their noncrystalline structure. In practice, glasses may contain appreciable amounts of crystalline material while other ceramics may have extensive noncrystalline or vitreous phases, so that the distinction between the two is not always clear cut.

Inorganic glasses are hard and brittle at room temperature, but become increasingly more fluid with rising temperature. At elevated temperatures they are liquids. The atoms of a liquid are not fixed in the structure, but can migrate and exchange partners with a considerable degree of freedom. As the temperature of a liquid is lowered, there is a constant adjustment of the mean atom positions. The atoms approach each other and their attractive forces increase correspondingly. At the melting point these forces tend to bring the atoms into some fixed relation to each other in an array which repeats itself throughout what has become a crystal. This long-range structural order is called a crystal lattice. In most substances this change occurs abruptly at the melting point. If, however, the movement of the atoms has become sluggish at the melting point, the temperature can be lowered further without adjustments other than those which

occur in the liquid phase. The substance is then a supercooled liquid. If the temperature can be lowered still further to a value at which a lack of mobility of the atoms precludes further adjustments, the prevailing structure is frozen in without crystallization and the substance is now a glass.

Investigation by means of x-ray diffraction has shown that the spectrum of a crystalline body consists of a series of well-defined lines which result from the regularity of the various atom spacings in the structure. For liquids the spectrum is diffused without the presence of lines. This denotes a lack of uniformity of atom spacings. In the case of glasses, the spectrum is diffused in the same manner as that of liquids.

Analysis of these spectrographic records has shown that for silica glass the atomic spacing of the nearest neighbors, between the Si and O atoms, is almost identical as in the corresponding silica crystal; but for more distant neighbors the spacings are no longer constant and become more variable as the distance between neighbors increases. From such work it has been concluded that the structure of glasses consists of a three-dimensional network, of which the basic unit is the silica tetrahedron, a silicon atom surrounded by four oxygen atoms. Adjacent tetrahedra are linked together by common oxygen atoms. The linkages between tetrahedra are slightly irregular, so that the long-range periodicity becomes lost. This structure of glass is called a random network.

CHANGES DURING COOLING

Although all physical properties change during the cooling process, those of dimension and viscosity are representative. Figure 1 compares the dimensional changes in a substance when it crystallizes and when it cools to a glassy state. Above the melting point it is a liquid with a relatively high coefficient of expansion with temperature. When it crystallizes at the melting point there is an abrupt decrease in dimension. At lower temperatures the rate of contraction is much lower than in the liquid state. If crystallization does not occur the contraction will continue as an extension of the liquid curve, and in this range the substance will be a supercooled liquid. For each rate of cooling a temperature will be reached at which the structural adjustments will lag behind the equilibrium of the liquid state. The curve AB shows this condition for rapid cooling. Below the point B no further structural rearrangements will occur and the substance is now a glass. The intercept E corresponds to the structural arrangement in the glass if it remained in equilibrium with the liquid. The temperature of the intercept T_f is known as the "fictive temperature." When cooled at a much lower rate, the substance remains a supercooled liquid to the lower temperature C and becomes a

FIGURE 2. Viscosity Relations versus Temperature of a Substance When Cooling from a Liquid to a Solid, and When Cooling to a Glass

glass at the point D. It has a fictive temperature T_f'. The temperature intervals AB and CD are called the transformation ranges for the two conditions of cooling.

The curves show that the dimensions of the glass, or specific volumes, are influenced by the rate of cooling through the transformation range. The higher the rate of cooling, the larger the specific volume.

Figure 2 illustrates the viscosity changes which occur on cooling. When crystallization occurs at the melting point, the viscosity rises abruptly, and further permanent deformation will result from plastic flow. As a supercooled liquid the viscosity rises rapidly as the temperature is lowered. The equilibrium condition is represented by the curve ACG. When cooled rapidly, the viscosity will follow the line AB and for slow cooling the line CD. Consequently, the viscosities of glasses are greatly affected by their rates of cooling through the transformation range. If the glasses are reheated to a temperature within the transformation range, the viscosity will shift toward the equilibrium condition by an amount depending upon the temperature and the time it is held there.

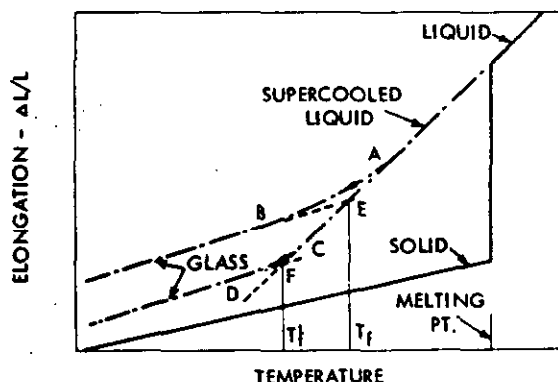FIGURE 1. Comparison of the Linear Contraction of a Substance When Cooling from a Liquid to a Solid, and When Cooling to a Glass

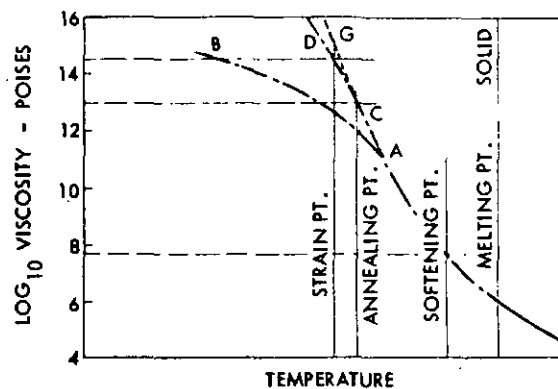In order to correlate the viscosity characteristics of different glasses, reference temperatures corresponding to specific viscosity values are used. These references are included in Figure 2. They are: strain point ($10^{14.5}$ poises), annealing point (10^{13} poises), and softening point ($10^{7.5}$ to $10^{8.3}$ poises). The strain and annealing points are measured at a cooling rate of roughly 4°C per minute. The points C and D indicate a slight departure of these viscosity values from those of the equilibrium curve.

COMPOSITION

6. Glassformers. Simple rules have been formulated to show the arrangement and linkage of inorganic compounds which permit them to produce uncrystallized or random networks on cooling. Although a number of oxides comply with these rules, the more important of these from the standpoint of commercial glasses are silica (SiO_2), boric oxide (B_2O_3), and phosphorous pentoxide (P_2O_5). Of these, silica is by far the most important. In addition, a very few oxide-free compounds will form glasses, but these are found only in special technical applications.

7. Modifiers. Although the above compounds can be used in one-component glasses, most compositions include other constituents. In oxide glasses these are other oxides. The oxygen ions enter the network, but the cations occupy spaces or holes in it. The lower bond strength of these cations tend to loosen the network. Some of the modifiers, soda (Na_2O) and potash (K_2O), act as fluxes to lower the temperature required to melt the glass. They also reduce the stability of the glass, but this can be improved with the addition of lime (CaO), magnesia (MgO), and lead oxide (PbO).

8. Intermediates. There is a third group of oxides which cannot act as glass formers alone, but which can enter the network of certain other glasses, and can produce desirable properties in them. Included in these oxides are alumina (Al_2O_3), zinc oxide (ZnO), and zirconia (ZrO_2). Alumina tends to prevent devitrification, while zirconia increases chemical durability.

9. Silicate Systems. The one-component glass of this system, silica glass, is difficult to manufacture so that its use is limited to special purposes. B_2O_3, another glass former, is sometimes added. It acts as a flux by reducing temperatures of melting, and also modifies other properties. In certain proportions, it maintains the thermal expansion coefficient at low values. Na_2O and K_2O are commonly used as fluxes, while CaO, MgO, and Al_2O_3 act as stabilizers. PbO increases density and refractive index and improves electrical properties.

TABLE I. CHEMICAL COMPOSITION OF COMMERCIAL GLASSES

No.	Designation	Constituents (Weight Percent)									
		SiO_2	Na_2O	K_2O	CaO	MgO	BaO	PbO	B_2O_3	Al_2O_3	Other
1	Silica Glass (Fused Silica)	99.5+									
2	96% Silica Glass	98.3	≤ 0.2	<0.2					2.9	0.4	
3	Soda-Lime (Window)	71 - 73	12 - 15		8 - 10	1.5 - 3.5				0.5 - 1.5	
4	Soda-Lime (Plate)	71 - 73	12 - 14		10 - 12	1 - 4				0.5 - 1.5	
5	Soda-Lime (Container)	70 - 74	15	1.0	5.0	4	0 - 0.5			1.5 - 2.5	
6	Lead-Alkali (Electrical)	63.0	7 - 7.5	6 - 7	0.3	0.2		21 - 22	0.2	0.5 - 1.0	
7	Borosilicate (Low Expansion)	81.0	4						13.0	2.0	
8	Aluminosilicate	57 - 62	1		8 - 10	7	0 - 6.0		5.0	15 - 17	
9	Solder Glass (High Lead)	3.0						75	11.0	11.0	
10	Glass Fibers (E Glass)	54.0			17.5	4.5			10.0	14.0	
11	Glass Fibers (Lime-Free)	59.5	14.5						7.0	5.0	ZrO_2, 4 TiO_2, 8

Table I lists representative compositions of a number of commercial glasses of the silica system.

a. Silica Glass. This is sometimes known under the commercial names of fuzed silica or fuzed quartz. It is essentially pure silica. This glass is low in thermal expansion coefficient, has high values of light transmittance, and has good electrical properties and chemical durability. It can be operated at higher temperatures than other silicate glasses.

A modification of this glass is known as 96 percent silica glass. It is made with a process which leaves a residue of about 3 percent of B_2O_3 in its composition. As a consequence, the viscosity characteristics are reduced materially. In general, its properties are slightly less desirable than those of the purer silica glass.

b. Soda-Lime Glasses. This type of glass is melted in larger quantities than any other glass. It is an economical glass to melt and to form into many products. It is widely used for glazing, for glass containers, and electric lamps of various types. Proportions of the various constituents of a soda-lime glass will vary over a relatively narrow range to make it most suitable for the particular forming operating used, and to meet the requirements of different products. For instance, chemical durability is of unusual importance for glass containers, while ease of lamp working and the ability to seal to certain other glasses for electric lamp enclosures is important for these types.

c. Lead-alkali Glasses. In these glasses, lead oxide may replace the lime of the soda-lime glasses, but in some of them the content of lead oxide may reach a value of 80 percent of the total. For most electrical applications, such as parts of incandescent lamp bulbs, the lead-oxide content is limited to about 20 percent. High lead compositions are used to absorb x- and gamma radiations, and as solder glasses for sealing other glasses at relatively low temperatures. Lead-alkali glasses are used for optical purposes and for decorative crystal because of their high refractive indexes.

d. Borosilicate Glasses. Although there are many glasses of this general type, one of particular interest is the low thermal expansion glass used for many industrial purposes. This glass has unusual resistance to thermal shock and has excellent properties of chemical durability.

The glass is well adapted for use in laboratory apparatus. It is free of heavy metal oxides, so that contamination is reduced in making chemical analyses.

e. Aluminosilicate Glasses. These glasses contain large amounts of Al_2O_3 and relatively large amounts of CaO and MgO. They are more highly viscous below 1,000°C than the more common glasses, so that they are suitable for higher operating temperatures. Thermal coefficients of expansion lie between those of the low-expansion borosilicate glasses and soda-lime glasses.

f. Glasses for Fibers. Although most commercial glasses can be drawn into fibers, chemical durability is of particular importance for most of these products, because many of the fibers range in diameter from values of less than one micron to ten microns. The two glasses listed in Table I have high resistance against weathering. High softening points are also desirable, because the cooling rates of fibers are extremely high, so that the viscosities will be depressed to much lower temperatures than when the same glasses are cooled slowly. This characteristic is shown in Figure 2. Textile products and thermal insulation are frequently operated at relatively high temperatures.

g. Other Glasses. Probably one thousand different commercial glass compositions are melted in any one year. Of these, a multitude of unusual compositions are used for optical purposes alone. Many others are used for technical and scientific purposes which demand special properties. New requirements in glasses arise from time to time, so that new compositions must be developed to meet them. Such glasses cannot be discussed within the scope of this manual.

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GLASS MANUFACTURE

10. General. The basic operations of glass manufacture include the fusion of the raw constituents into a molten mass and then the forming of the viscous mass into desired shapes.

11. Raw Materials. The constituents which are combined to form the batch may include many raw materials. Table II lists only some of the more common ones. The list indicates not only the glassmaking oxide available in each material, but also the proportion present.

Of these materials sand, limestone, dolomite, and feldspar are natural minerals, although they may be processed to a minor extent to increase their purity or convenience. In better quality sands, the desired iron content may be not more than 0.025 percent, so that some sands are treated to lower the iron content. Other materials may be processed to some degree. Soda ash, potassium carbonate, litharge, and zinc oxide are all processed materials. Several sources can usually be used for any constituent, and substitutes are sometimes made without appreciable modifications of either chemical composition or

TABLE II. GLASSMAKING MATERIALS

Raw Material	Chemical Composition	Glassmaking Oxide	Percent of Oxide
Aluminum hydrate	$Al_2O_3 \cdot 3H_2O$	Al_2O_3	65
Barium carbonate	$BaCO_3$	BaO	78
Borax	$Na_2B_4O_7 \cdot 10H_2O$	B_2O_3	36
		Na_2O	16
Dolomite	$CaCO_3 \cdot MgCO_3$	CaO	30
		MgO	22
Feldspar	$K_2(Na_2)O \cdot Al_2O_3 \cdot 6 \, SiO_2$	Al_2O_3	18
		$K_2(Na_2)O$	13
		SiO_2	68
Limestone	$CaCO_3$	CaO	56
Litharge	$Pb\,O$	$Pb\,O$	100
Potassium carbonate (calcined)	K_2CO_3	K_2O	68
Sand	$Si\,O_2$	$Si\,O_2$	100
Soda ash	Na_2CO_3	Na_2O	58
Zinc Oxide	ZnO	ZnO	100
Zirconium oxide	ZrO_2	ZrO_2	100

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properties of the glass melted. The use of dolomite is restricted to those glasses in which MgO is acceptable as a minor constituent.

Many raw materials are used as colorants in melting colored glasses, and still others for reducing agents and fining agents. (Fining agents accelerate the fining operation.)

The raw materials are received, inspected, and stored. Batch calculations determine the proper weight proportion of each material required, and the batch constituents are weighed to conform to these computations. Waste glass obtained from melting and forming operations and known as cullet is commonly added to the batch. The batch is then mixed and prepared for charging into the melting unit.

12. Melting. Melting consists of raising the temperature of the batch, usually from 1,400 to 1,600°C, where chemical changes occur in the raw materials and the glassmaking oxides become molten. Gases are liberated which may pass off in the exhaust gas of the furnace, or remain as bubbles or dissolved in the glass. The fining operation, then carried out at a somewhat reduced temperature, allows most of the entrained gas to escape or redissolve in the glass. Fining also brings the glass to a more homogeneous condition by reducing striae or cords.

All major melting operations are now carried out in continuous tanks, in which both the operations of charging of the batch at one end and the withdrawal of the fined glass at the other end are continuous. These tanks are large rectangular troughs, the larger of which may exceed 100 feet in length and may hold 1,500 tons of glass. This holding capacity may represent the output of one to seven days, depending upon the type of glass and the degree of fining required by the product. The bottom and side walls are constructed of large refractory blocks and the crown of refractory bricks.

Fuels commonly used are natural gas or oil. In the larger tanks the burners enter through the side walls, which are also provided with ports

to permit the removal of waste gases. The fuel and air required for combustion are preheated in regenerator units made up of refractory bricks, which are heated by the waste gases.

Molten glass is a relatively good conductor of electricity. Melting operations may be performed with electric currents passed through the body of the glass. In small tanks intended for special glasses, practically the entire melting energy may be supplied electrically. In large units, electric power when used is more commonly an auxiliary source for the closer control of temperature and viscosity, as the glass is being conditioned for forming operations.

The back end of the tank is used for charging the batch and melting it, while the front end is used for fining. A refractory bridge wall across the tank, with an opening for the circulation of glass, sometimes separates these two operations. From the fining end the glass passes into a channel or forehearth to the forming equipme ... In this part of the tank, the glass is brought to the viscosity required by the particular forming operation in use.

13. Primary Forming Operations. These are operations in which the glass is formed directly as it is drawn from the melting unit. They include rolling, drawing, pressing, blowing, and casting.

a. Rolling. Glass is allowed to flow from a broad channel to the space between two large steel rolls placed before the lip of the channel. The thickness of the plate, determined by the spacing between the rolls, is commonly between 1/8 inch and 1-1/4 inches. The plate is conveyed on rollers to an annealing lehr or oven. Plate glass, patterned glass, and wired glass are all produced by this method.

b. Drawing.

(1) Sheet. Sheet glass for glazing and other uses is produced by drawing the sheet upward from a pool of molten glass. The original process was known as the "Fourcault process," although several modifications are now in use. The form of the sheet must be stabilized, as the sheet leaves the pool. In the Fourcault process, it is

drawn through an elongated slot in a partly submerged refractory bar, called a "debiteuse." The glass is annealed either while it is drawn upward, or after bending over a roll into a horizontal position.

Commercial sheet glass is ordinarily made in thicknesses between 0.05 inch and $\frac{1}{4}$ inch. With special equipment, sheet glass in narrow widths can be drawn in thicknesses between 0.001 inch and 0.010 inch.

(2) Tubing. Tubing is also formed by means of drawing processes. In some equipment the tubing is drawn upward from a refractory cone submerged in the glass. It is fully, or partially annealed as it passes upward to an upper level, where it is cut to lengths. This process is well adapted to making large tubing up to eight inches or more in diameter. A modification is also used for drawing thermometer tubing, which is of small diameter.

In another process, the glass is drawn downward through the annular space between a mandrel and a ring, both of refractory material. A third process draws the tubing from an inclined refractory mandrel fed with a stream of glass.

(3) Glass Fibers. Glass fibers are drawn through small orifices distributed along the bottom of a platinum trough or bushing, which is heated electrically. In the manufacture of certain products, these bushings are attached to the bottom of a larger melting unit. The drawing forces may be produced by jets of air, steam, or flame. These fibers are of limited length and are called staple fibers. In making other fibers, selected glass cullet is remelted in the platinum bushings. Many continuous filaments are drawn in a single strand by means of mechanical winding machines. These continuous filaments are used mainly for textile products and for reinforcement of plastic materials.

The quality of glass, particularly for continuous filaments, should be good because inclusions and bubbles can interfere seriously with drawing operations.

c. Pressing. In this operation, a mass of glass called a gob is severed from the stream drawn from the tank and dropped into the press mold. The device which performs this operation is known as a gob-feeder. A mechanism produces an intermittent flow of the glass stream from a forehearth of the tank, while the action of the shears cutting the stream and the motion of the turntable of the press carrying a series of molds are coordinated with pulsations of the stream. The weight of the gob sheared in this manner can be controlled within close limits.

The motion of the turntable brings the molds with their gobs successively under a metal plunger, which moves downward to force the viscous gob into the cavity between the mold and plunger. The closure of this cavity is effected by a third mold element called a ring. After the glass has set up, the plunger is withdrawn. This is made possible by a small taper on the sides of the plunger.

When the turntable has moved forward several positions, the pressed glass is raised from the mold and conveyed to the lehr. If the mold is machined from a solid piece of steel, the sides must be tapered, but if the mold is hinged so that it can be opened this taper is not necessary. Large quantities of heat are taken up by the mold and plunger in the pressing operation, so that provisions must be made to cool them.

Pressed articles are made in sizes ranging from pieces weighing a fraction of an ounce to those weighing 35 to 40 pounds.

d. Blowing. Air is first blown into a glass blank or parison to produce a cavity. This parison is then inserted into a blow mold, where a second blowing operation is performed to expand the cavity until the glass is forced against the walls of the mold. There are many variations of these operations, depending upon the form of the article being blown and the type of equipment used. Hand-blowing is still used for the limited production of special articles.

The mechanized production of glass containers, mainly bottles, represents the most extensive use of the blowing operations. Two

methods in common use vary mainly in the manner in which the glass is fed to the parison mold. In the Owens method the parison mold, held at the mouth of the bottle or "finish" end, and open at the bottom, is dipped into a rotating pot of molten glass. The glass is sucked into the mold and the bottom is closed off. A puff of air through the finish end forms a small cavity, after which the parison mold is then removed, while the glass is still held at the finish. The glass is then transferred to the hinged blow mold, which closes, so that the glass is then blown to fill this mold. The mold is opened and the bottle is removed and conveyed to the lehr.

The other method uses the gob-feeder already described under <u>Pressing</u>. The gob is dropped against the finish end of the parison mold, while a puff of air from above compacts the gob to form the finish of the bottle. The other end of the mold is then closed and the cavity is formed by a counter blow through the finish end. The transfer to the blow mold and the final blowing in this mold are similar to corresponding operations of the Owens method. An important feature of both methods is the complete forming of the finish in the parison mold, which eliminates any tooling, as was the case in the old hand-blowing method. The parison of a wide-mouth jar is commonly formed in a press mold before its transfer to a blow mold.

Bulbs for incandescent lamps are blown with entirely different equipment called a "ribbon machine." Glass from the melting unit is fed continuously between a pair of forming rolls, and the ribbon thus formed travels forward on a series of moving steel plates. Corresponding blow heads, moving at the same speed, puff the glass through holes in the plates, after which the hollow glass parisons continue to elongate. Blow molds in two parts, also moving forward, close around the parison and rotate while the glass is blown into them. As the molds open, the bulbs are removed from the glass ribbon and pass to the lehr. The inner surfaces of the molds are coated with a moist material, referred to as paste, which produces a clear, smooth surface on the bulb. A single ribbon machine can produce as many as 2,000 per minute of bulbs of certain sizes.

e. Casting. One method of casting is used in the production of massive optical components. Selected pieces of cullet are placed into a refractory mold, and the mold and glass are then heated in a furnace until the glass melts. The temperature is reduced at an appropriate rate to anneal the glass. In some instances where the glass is melted in a small continuous tank, it may be loaded into the mold in a stream. Both mold and glass are held at an elevated temperature during this operation.

Hollow glass shapes, such as funnels and cylinders, are sometimes formed by a centrifugal casting process. A gob-feeder loads the glass into the mold. The mold is then rotated at a speed which will force the glass against the wall of the mold, causing it to rise to the open end. When the glass has set up, the mold is stopped and the glass is removed.

14. Secondary Operations. Secondary operations are carried out after the glass has been formed at the melting unit. A great number of such operations have been developed to bring the glass to its finished condition.

a. Secondary Forming. Extensive operations are performed with the lamp-working methods to produce special and complicated shapes from tubing and other articles. The glass is heated locally and reformed by bending, blowing, repressing, and sealing. Many types of laboratory and scientific ware are fabricated in this manner. Large parts which cannot be formed conveniently by primary operations are frequently sealed together in a lathe, using large gas burners to heat the regions to be sealed. In some cases, thick sections are heated by electric currents passed through the glass in order to bring it to sealing temperatures. The currents are conducted to the glass by means of electric arcs.

Flat glass is bent over a form or sagged by heating it to a high temperature.

Glass parts of special shapes are sometimes formed from powdered glass to which a small amount of organic binder has been added. This material is dry-pressed and then sintered at elevated temperatures. This method is convenient for small articles with holes.

In a recently developed process, flat glass is taken from the rolls and floated across the surface of a bath of molten metal. The temperature of this metal is sufficient to heat-polish the glass in contact with it. A flame above the glass fire polishes the opposite surface. In this manner the operations of mechanical grinding and polishing are eliminated. The product is known as "float-glass."

b. Annealing and Tempering. The technical problems involved in these processes are reviewed elsewhere. If glass is allowed to cool freely in air after forming, internal stresses will be set up, which under some conditions may cause breakage. These stresses can be reduced to an acceptable value by controlled cooling or annealing. Furnaces used for this purpose are called lehrs.

One method is to place the glass in an oven or furnace, bring the glass to a temperature usually at or slightly above its annealing point for a short period of time, and then allow the temperature to drop to a second temperature (usually slightly below the strain point of the glass), at a rate which will prevent excessive stresses from being set up. More frequently the lehr consists of a long tunnel with a moving conveyor belt. The temperature distribution along the axis of the furnace is such that when the conveyor belt is operated at a suitable speed, the desired annealing conditions are met. The temperature and speed of the belt will depend upon glass composition, thickness of the sections of the glass, and the allowable values of its internal stresses.

For tempering, the cooling rates used are much higher than for annealing, so that the internal stresses of the glass are greater. This condition, known as prestressing, increases the resistance of the glass against applied forces. The temperature of the glass is raised to a value usually near its softening point, and it is then chilled by blasts of air or by other means of cooling. It is important that all surfaces of the glass be in compression, otherwise the article will not be properly strengthened.

c. Grinding, Polishing, Cutting. Grinding is sometimes used to remove excess glass or to produce flat or accurately formed surfaces. These operations may be performed with loose abrasive on a grinding mill, bonded abrasive wheels, or with diamond-impregnated wheels. Copper wheels fed with abrasive powder are used for engraving glass.

The roughening of the glass surface by the abrasive grains is often undesirable, so that polishing is used to restore it to a smooth condition. Mechanical polishing with rouge (ferric oxide) or ceric oxide, applied to the surface with a moving lap or buff, is widely used. Other means of polishing include the use of a flame (fire-polishing) and etching with dilute hydrofluoric acid. All of the above methods are used to strengthen glass surfaces which have been weakened by grinding or other treatment.

In the conventional grinding process for plate, the glass is carried from the lehr on a conveyor to a series of grinding mills. The mill wheels are in a horizontal plane (vertical axis), in pairs, so that one is above and one below the glass. Sand is used as loose abrasive, in finer grains for successive mills. When the grinding operation is complete, the plate is passed between rotating laps for polishing.

Flat glass is cut to desired dimensions with small edged scoring wheels drawn across the glass surface. The deep cracks caused by this operation can also be produced with a cutting diamond, but these are now little used commercially.

d. Enameling. The covering of glass surfaces with vitreous enamels is one of the secondary manufacturing operations of this material. Other related uses of enamels or glazes include the glazing of ceramic bodies and the coating of steel or other metals with these enamels. The enameling of metals to improve their appearance or sanitary properties and to prevent chemical attack is a separate industry, with its own technical and production problems. (Information on this subject can be found in Reference [10], section 26-12.)

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Clear glass articles are coated with opaque enamels for purposes of decoration, for printed information, and to control light (lighting globes and colored panels for buildings). Glass can also be prestressed by suitable glazes. Enamels should have a firing or maturing temperature below that which will cause the glass substratum to deform. Except when used for prestressing, the enamel should have the same thermal expansion characteristics as the base glass, or slightly lower. In order to reach a low softening point the enamels usually include appreciable amounts of lead oxide or boric oxide. Opacifiers, such as titanium dioxide or molybdic oxide are added, and also coloring oxides. These enamels are milled to a finely divided form. When obtained in dry form they are mixed with gum spirits of turpentine or other oil to make a paste which can be applied with brush, spray, or with printing screens. After drying, the coated glass is passed through a decorating lehr, which may reach a peak temperature of about 600°C. The rate of cooling must permit the annealing of the glass.

For purposes of prestressing, the vitreous coating must have a thermal coefficient of expansion materially lower than that of the base glass. The compression glaze must cover the entire surface of the base glass, otherwise stress concentrations will occur at discontinuities. This method of prestressing is also applied to glass-ceramics.

Glass 9 of Table 1 is for a "solder glass," that is, a glaze used for sealing together two glasses, or a glass and a metal. This glass has a softening point of 440°.

e. *Special Processes - 96 Percent Silica Glass.* Among the many special processes developed for glasses the method of producing 96 percent silica glass is of considerable interest. The desired ware is formed oversize from a somewhat unstable glass composed of silica and boric oxide. This glass is subjected to a heat treatment which produces phase separation; that is, two different glasses are mingled in the body, one essentially silica and the other essentially boric oxide. The boric oxide phase is leached out in acid, leaving a porous structure of silica. This skeleton structure of 96 percent silica is

heated to a temperature which causes the pores to collapse. The body is thus consolidated and shrinks so that all dimensions are reduced by some 14 percent.

(1) Prestressing by Ion Exchange. The commercial use of principles of ion exchange on glass surfaces for the purpose of prestressing is of recent origin. The glass is immersed in molten alkali nitrates at a temperature below the transformation range of the glass [11]. In such a bath the lithium atoms of a glass may be replaced with the larger sodium atoms, or the sodium atoms with the larger potassium atoms. Ion exchange moves inward from the surface by diffusion processes, so that the depth of the exchange will vary with the square root of the time duration of the process. Under practical conditions this depth is usually limited to about 0.010 inch. Best results are obtained with glasses with compositions developed particularly for this purpose.

When the glass is cooled the larger ions become wedged in the surface so that high compressive stresses, often of the order of 50,000 psi, will result. If the ion exchange does not change the thermal coefficient of the glass appreciably, these compressive stresses will be retained until the strain point of either the base glass or the compressive layer is reached.

(2) Devitrification. A perfect glass will be completely noncrystalline. Practically, fine crystals may be grown in certain glasses to produce or control color, and in some opal glasses for opacity. Special procedures are employed in photosensitive glasses to produce small nuclei or larger crystals. These general principles have been developed and expanded in recent years for the purpose of devitrifying glass bodies so that they are largely, and sometimes almost completely, crystalline. The resulting products are called glass-ceramics [12].

The compositions of the glasses used for devitrification contain certain nucleating agents or catalysts for accelerating the operation. These nucleating agents may be metallic colloids (Au, Ag, Cu, Pt) or TiO_2, P_2O_5, or ZrO_2 [2]. After

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the glass is melted and the article formed in the usual manner, it is held at a temperature at which the catalyst is homogeneously nucleated.* Then, in a second heat treatment, these small crystals become heterogeneous nuclei for another crystalline phase which includes the major constituents of the glass. Relations between these growth rates and temperature are shown in Figure 3. The crystals formed in this way are small, usually with dimensions of the order of 100Å ($10\,m\mu$), although under certain conditions they may be grown to much larger sizes.

With some glass compositions the crystallization process can be continued until practically

RATES OF GROWTH AND FORMATION

FIGURE 3. Crystallization Properties of Glass-Ceramics (after Stookey, Reference [12])

the entire body is devitrified. In other cases two or more different crystal phases may be formed, usually at different temperatures, so that complete devitrification may be less simple. Another practical limitation in glass composition results if appreciable changes in volume occur during the devitrification process. In general, the linear change of dimension should not exceed 0.5 percent.

If the temperature of a glass-ceramic is raised above the liquidus of the material, it will revert to a glass.

f. Secondary Operations on Glass Fibers. Glass fibers are processed into two basic classes of products, one consisting of wool in the form of insulating bats and bonded mats or packs, the other being textile products. Blown staple fibers are collected on conveyors in felted form. Lubricants or bonds may be sprayed into the fibers while they are being collected on the conveyor. For some purposes the bonding material is added in later operations, sometimes by dipping, and some of these bonds are cured with heat. The density of the wool can be increased greatly when the fibers are held with these bonds, so that its properties are improved for thermal insulation at higher temperatures, and for structural purposes in the form of boards. High density is also desirable for other applications, such as sound absorption.

Textile fibers are of two types, staple fiber and continuous filament. Staple fibers are blown and laid down in the form of a light webbing which is collected as a sliver. The sliver is further drafted and twisted into yarns. The continuous filament strands are combined and twisted into yarns. Textile operations of conventional types are used for fabricating the yarns into many products such as cord, cloth, tape, and braided tubing.
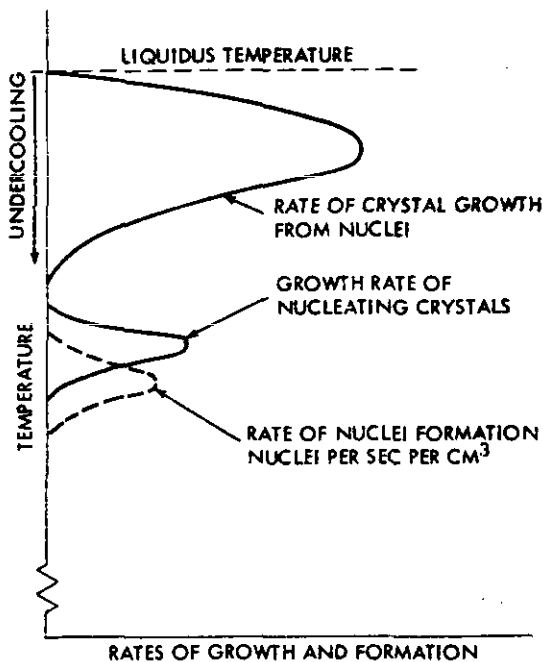
*For further discussion on nucleation see Reference [4], Chapter 10.

When used for electrical insulation, the glass textiles are impregnated with varnishes. In order to raise temperature limits thus imposed, high temperature varnishes such as silicones are used for this purpose.

Textile fibers are processed in a number of forms for the reinforcement of plastic bodies; continuous filament strands, either in long lengths or chopped into short lengths, roving, cloth, and filled mats are all used for this purpose. In this procedure special textile sizing materials called coupling agents are used on the glass, in order to increase the adhesion between the glass and the plastic.

Chapter 3
Selection Criteria (Properties)

INTRODUCTION

The properties of a material define its characteristics and determine its suitability for possible uses. Certain characteristics of glass differ materially from those of common engineering materials, so that the subject of its properties assumes more than ordinary importance. Properties are discussed in more detail in the general references (such as Reference [6].)

VISCOSITY

The general relationship between viscosity and temperature was indicated in Figure 2. A convenient means of distinguishing these characteristics is the use of reference temperatures corresponding to specific values of viscosity

and measured under standard conditions. These terms, their viscosity values and the standard test specifications, are indicated in Table III.

The temperature interval between the annealing point and the strain point represents a nominal annealing range of the glass. The softening point is a measure of the temperature at which the glass will deform readily under its own weight. The working point corresponds roughly with a viscosity which is suitable for various forming operations. These reference temperatures are listed in Table IV, Physical Properties of Commercial Glasses. Viscosity curves of these same glasses are given in Figure 4. It is noted that the viscosity values of silica glass and 96 percent silica glass show some spread. This

TABLE III. REFERENCE TEMPERATURES IN RELATION TO VISCOSITY AND TEST SPECIFICATION

Reference Condition (defined as a temperature)	Approx. Viscosity (Poises)	Test Specification
Strain point	$10^{14.5}$	ASTM Desig. C336
Annealing point	$10^{13.0}$	ASTM Desig. C336
Softening point*	$10^{7.5}$ to $10^{8.3}$	ASTM Desig. C338
Working point	10^4	-----

* In this test the glass elongates under its own weight so that the viscosity value depends to some degree upon glass density.

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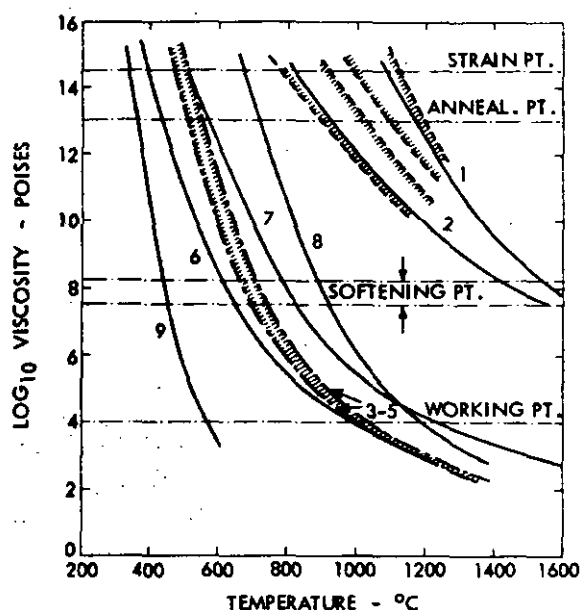
FIGURE 4. Viscosity Characteristics versus Temperature of Commercial Glasses. Numbers on curves correspond to those of Tables I and IV

variation results from very minor constituents in the glass and sometimes from thermal treatment.

DENSITY

The density of glass is commonly expressed in grams per cubic centimeter, which corresponds closely to its specific gravity. For purposes of comparison these measurements are made at room temperature.

The density of silica glass is 2.203 gm/cm3, which is not greatly different from that of its crystalline form of cristobalite (2.320 gm/cm3). As other constituents such as modifiers are added to silica, some of the atoms will accommodate themselves to interstices in the random network, so that the specific volume of the glass may not change correspondingly. Boric oxide glass has a density of roughly 1.84 gm/cm3, so that some borosilicate glasses can be lower in density than silica glass. Glasses of extremely high contents of lead oxide may reach density values in excess of 6 gm/cm3.

Figure 1 has shown that when a glass is quickly chilled from the supercooled liquid state it will have a greater specific volume (lower density) than when it is well annealed. Except for fibers this difference is only a small fraction of one percent.

Table IV gives density figures for a number of glasses.

EXPANSION WITH TEMPERATURE

The coefficient of thermal expansion determines the magnitude of the stresses developed by temperature differences within a body. When seals are made between two pieces of glass, or between glass and metal, the difference in thermal expansions establishes the magnitude of stresses set up when the composite body reaches room temperature.

Thermal expansion is determined by measuring the differential elongation between the glass
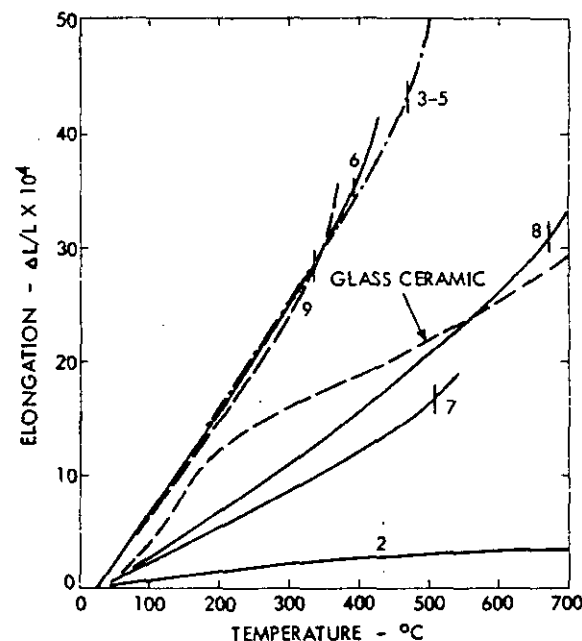
FIGURE 5. Relative Elongation versus Temperature of Commercial Glasses and One Glass-Ceramic. Vertical intercept shows strain point of glasses. Numbers are those of Tables I and IV

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TABLE IV. PHYSICAL PROPERTIES OF COMMERCIAL GLASSES

No.	DESIGNATION	Viscosity Reference Temps. (°C)				Thermal Expansion Coeff. (Per °C x 10⁷)		Density (gm/cc)
		Strain	Anneal	Soften	Working	$0-300^{\circ}C$	Room Temperature to Setting Pt.	
1	Silica Glass (Fused Silica)	1070	1140	1667	—	5.5	7.0	2.20
2	96% Silica Glass	820	910	1500	--	8.0	7.0	2.18
3	Soda-Lime -- Window	505	548	730	1010	85.0	--	2.46
4	Soda-Lime -- Plate	510	553	735	to	87.0	--	to
5	Soda-Lime -- Container	505	548	730	1060	85.0	--	2.49
6	Lead-Alkali -- Electrical	395	435	626	985	93.0	100.0	2.85
7	Borosilicate -- Low Expansion	515	565	820	1245	33.0	35.0	2.23
8	Aluminosilicate	670	712	912	1185	42 - 46	53.0	2.60
9	Solder Glass (High Lead)	340	365	440	560	84.0	92.0	5.42
10	Glass Fibers (E Glass)	--	--	830	--	60.0	--	2.60
11	Glass Fibers (Lime Free)	--	--	675	--	75.0	--	2.57

No.	DESIGNATION	Refract. Index (0.5893μ)	Vol. Resistivity (Log_{10} ohm-cm)		Dielect. Property (1 mc, 20°C)		Elastic Property	
			250° C	350° C	Dissip. Factor	Diel. Const.	Elast. Modulus (10^6 psi)	Poisson Ratio
1	Silica Glass (Fused Silica)	1.459	12.0	10.0	0.00001 to 0.0002	3.8	10.5	.16
2	96% Silica Glass	1.458	9.7	8.1	0.0005	3.8	10.0	.19
3	Soda-Lime -- Window	1.510	6.5	5.2	0.004	7.0		
4	Soda-Lime -- Plate	to	to	to	to	to	10.0	.21
5	Soda-Lime -- Container	1.520	7.0	5.8	0.011	7.6		
6	Lead-Alkali -- Electrical	1.539	8.9	7.0	0.0016	6.7	8.9	.21
7	Borosilicate -- Low Expansion	1.474	8.1	6.6	0.005	5.1	9.1	.20
8	Aluminosilicate	1.540	12.5	10.5	0.0025	6.7	12.6	.25
9	Solder Glass (High Lead)	--	10.6	8.7	0.0022	15.0	8.0	.28
10	Glass Fibers (E Glass)	1.550	--	--	--	--	12.0	--
11	Glass Fibers (Lime Free)	1.540	--	--	--	--	--	--

and some material of known expansion, such as silica glass, over a range of temperature. For experimental purposes the temperature is raised from room temperature, usually 25°C, to values above the strain point of the glass. The overall elongation, expressed as a fraction of the room-temperature dimension, is then plotted as a function of temperature. Figure 5 includes elongation curves for a number of commercial glasses and one glass-ceramic body. The curves for glasses are approximately linear to some temperature below the strain point, which is indicated by the short vertical intercept on the curves. Within the transformation range the slope increases, until at the annealing point it may be two or three times greater than at low temperatures.

The mean coefficient of thermal expansion from room temperature to any other temperature is obtained by dividing the elongation at this temperature by the temperature difference.

For comparison of glasses and for control of glass properties during melting operations, a simpler procedure is used. The temperature of the glass specimen is raised from 0°C to 300°C, and the overall elongation is read from a dilatometer. The coefficient of thermal expansion is commonly expressed in parts per 10 million per °C. Procedures for this test are given in ASTM Desig. C337. Values from this type of test, and also mean values from room temperature to a temperature 5°C above the strain point, are included in Table IV.

SPECIFIC HEAT AND THERMAL CONDUC-TIVITY

Glasses fail to crystallize at a melting point, so that there is no measurable latent heat of melting. There are also no sudden polymorphic changes at specific temperatures, such as are found in the various forms of silica which cause abrupt changes in heat capacity. Structural changes continue to occur gradually in glasses until the lower end of the transformation range is reached (and time is a factor determining these changes). Glasses are metastable bodies, so that the minimum values of heat content represented by corresponding crystalline forms are never attained.

Because of these conditions, the changes of heat content and thus the specific heats of glasses

are not unique quantities at any temperature, but will depend to some degree upon test procedures. Considering Figure 1, the heat content of the glass as represented by condition B will differ from that represented by D, so that corresponding changes of heat content measured to some temperature above the transformation range will differ materially. Data on specific heats of glasses are subject to some variation.

True specific heat is expressed in gram-calories per gram for a 1°C change of temperature. The mean specific heat is the average value of true specific heat taken over the temperature interval considered. Data for the true specific heats of representative glasses are included in Table V.

TABLE V. DATA FOR TRUE SPECIFIC HEATS OF REPRESENTATIVE GLASSES

Glass	True Specific Heat (cal x gm^{-1}x ^{o}C^{-1})			Thermal Conductivity (cal x sec^{-1}x cm^{-1}x ^{o}C^{-1*})		
	0°C	200°C	400°C	0°C	200°C	400°C
Silica glass	0.16	0.23	0.26	0.0035	0.0042	0.0047
96% Silica glass	--	--	--	0.0030	0.0040	0.0042
Soda-Lime	0.18	0.25	0.29	0.0024	0.0030	0.0034
Lead-Alkali	0.15	0.19	0.22	0.0016	0.0029	--
Borosilicate (low expansion)	0.17	0.24	0.28	0.0028	0.0032	0.0037
Aluminosilicate	0.17	0.23	0.27	--	--	--
Glass-Ceramic	0.18	0.24	0.27	0.0087	0.0085	0.0077

* To convert thermal conductivity values to Btu x hr^{-1} x ft^{-1} x ^{o}F^{-1}, multiply by 241.

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Thermal conductivity data, expressed in terms of gram-calories per second per square centimeter per °C for a section 1 centimeter thick, or calories x seconds^{-1} x centimeters^{-1} x °C^{-1}, are also listed in the table.

At temperatures above 400°C, the rate of heat transfer will be increased by radiation effects occurring within the body of the glass.

EMISSIVITY

Emissivity is the ability of a body to radiate heat energy considered as a ratio of that radiated by an ideal black body. It can be expressed for any specific wavelength or as total emissivity, which includes all wavelengths. The emissivity of glasses at the longer wavelength (low temperatures) is high. Data for a soda-lime glass are given in Table VI. The effect of thinner sections is to increase the transmittance of the glass and thus reduce its emissivity.

MECHANICAL PROPERTIES

15. Elasticity. When viscosity values exceed 10^{15} poises, the flow of glass is so slight that deformations are essentially elastic. For practical purposes glass may be considered as an

isotropic solid. The elastic constants of such a solid are related as follows:

$$G = \frac{E}{2(1 + \nu)} \qquad (1)$$

$$K = \frac{E}{3(1 - 2\nu)} \qquad (2)$$

$$\nu = \frac{E}{2G} - 1 \qquad (3)$$

where E is the elastic modulus, G is the modulus of rigidity, K is the bulk modulus, and ν is Poisson's ratio.

Table VII lists the elastic constants of common glasses at room temperature.

The moduli of most glasses tend to decrease slightly with temperature. Exceptions to this are the two silica glasses and the borosilicate glass, all of which have high proportions of network atoms.

Glasses exhibit appreciable elastic after-effects, even at room temperature. They are smaller in silica glass than in other glasses.

TABLE VI. TOTAL EMISSIVITY OF SODA-LIME GLASS (PERCENT)

Temperature (°C)	THICKNESS		
	1/8 in.	1/4 in.	1/2 in.
250	(89)*	91	92
450	(82)*	88	90
550	70	83	88

* Values in parentheses are extrapolated.

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TABLE VII. ELASTIC CONSTANTS OF COMMON GLASSES

Glass	Elastic Modulus (E in 10^6 psi)	Modulus of Rigidity (G in 10^6 psi)	Poisson's Ratio
Silica glass	10.5	4.5	0.16
96% Silica glass	10.0	4.2	0.19
Soda-Lime (plate)	10.5	4.3	0.21
Soda-Lime (bulb)	10.0	4.0	0.24
Lead-Alkali (20% PbO)	8.9	3.7	0.21
Borosilicate (low expansion)	9.1	3.8	0.20
Aluminosilicate	12.5	5.0	0.25
Glass-Ceramic (medium expansion)	17.4	7.0	0.24

TABLE VIII. DIAMOND PYRAMID HARDNESS OF GLASSES

(Load 100 grams, room temperature)

Glass	Hardness (kg/mm^2)
Silica glass	700-750
96% Silica glass	650-700
Soda-Lime (plate)	540-580
Lead-Alkali (30% PbO)	420-470
Borosilicate (low expansion)	550-600
Aluminosilicate	600-650
Glass-Ceramic (medium expansion)	620-640

16. Hardness. Hardness of materials can be measured in various ways, depending upon how this property is defined. Indentation hardness tests have been made successfully on glasses, using a pointed diamond indenter. These hardness values are expressed in terms of the load in kilograms divided by the area of the impression in square millimeters. Data obtained by different investigations are not entirely consistent, but representative values are listed in Table VIII.

17. Strength.* The subject of strength of glass is one of major importance. Although complex, it is also of pronounced technical interest. Glass is a brittle body, probably more brittle than any material in common use. It breaks suddenly without prior yield or plastic deformation. Failure is caused by a component of tensile stress, even when the material is loaded in compression. Fracture originates at a flaw and the nominal strength of the glass is determined by the severity of this flaw. In commercial glassware the weakening flaws are of accidental origin and vary greatly in severity from piece to piece in the same group, consequently there are wide variances in measured values of their breaking stress; see paragraph d, Variance of Breaking Stresses, and Figure 9.

a. Brittle Fracture. When an elastic body is subjected to stresses, elastic energy is stored in the body. In any small volume of material this energy is proportional to the square of its stress and inversely proportional to its elastic modulus. When fracture occurs, work is consumed in producing and enlarging the fracture crack. In a perfectly brittle body this work is equal to an energy value proportional to the increased surface area of the crack. For ductile bodies the work of plastic deformation of the highly stressed region immediately around the crack may be many times that of its surface extension. The criterion for fracture is that the crack will propagate when the release of elastic strain energy exceeds the total work done in forming the new surfaces. When this criterion is reached in the brittle bodies, fracture will occur suddenly and completely. Glass conforms generally to the behavior of a perfectly brittle body.

Equations expressing the criterion of brittle fracture can be modified to show that fracture occurs when the concentrated stress in a crack reaches a critical value identified with the intrinsic strength of the material. Attempts have been made to measure this intrinsic strength by testing specimens which are devoid of cracks and imperfections to the highest degree possible. Small fibers drawn under conditions to produce smooth surfaces have been found to break at stresses from one-half million to one million psi. Consequently, the intrinsic strength must reach these values, at least.**

Nominal breaking stresses of commercial glassware are commonly of the order of 10,000 psi. This means that the flaws or imperfections in such ware must produce high stress concentration factors (sometimes approaching factors of 100). This is explained by the fact that characteristic flaws are extremely narrow in relation to their depth. It is found that a flaw 0.0025 inch deep can reduce the breaking stress of glass to values of the order of 10,000 psi.

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*Many discussions of this subject are available, such as the General Survey [13], Anderson [14], Berry [15], and Weil [16].

**Values of almost 2×10^6 psi for silica at $78°K$ are reported by Hillig [13], and 1×10^6 psi for silica at room temperature by Morley, Andrews, and Whitney [13].

b. *Stress Fatigue.* When glass and other brittle materials are subjected to stress in the presence of air, the breaking stress for a load of short duration will exceed that for one of long duration. This is known as delayed fracture, or static stress fatigue. For a delay of a fraction of one second, the breaking stress may be more than double that for a delay of several hours or several days. There is some low value of stress which will not produce fracture, even when sustained for an indefinite period of time. This stress is known as the endurance limit or fatigue limit. Static fatigue differs from cyclic fatigue experienced in metals, because it is a function of load duration and not of the number of stress cycles.

Figure 6 shows a representative curve for static fatigue for a glass specimen (A), tested in air. The fatigue limit is about 45 percent of the one-second strength. Curve C, for similar specimens tested in a vacuum, shows no appreciable fatigue effects. This is also true for specimens tested in air at low temperatures (180°C).
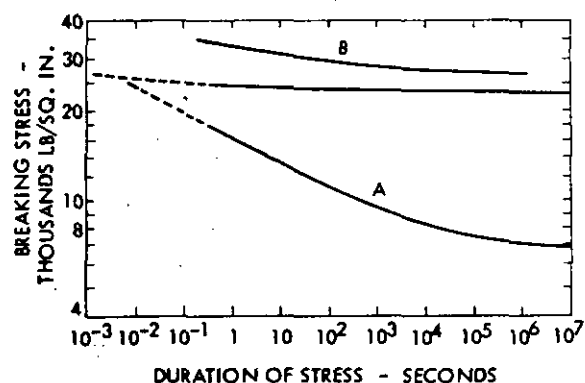

FIGURE 6. Stress-Time Characteristics of Glass Broken in Flexure Tests at Room Temperature. A, annealed glass in air; B, tempered glass in air; C, annealed glass in vacuum
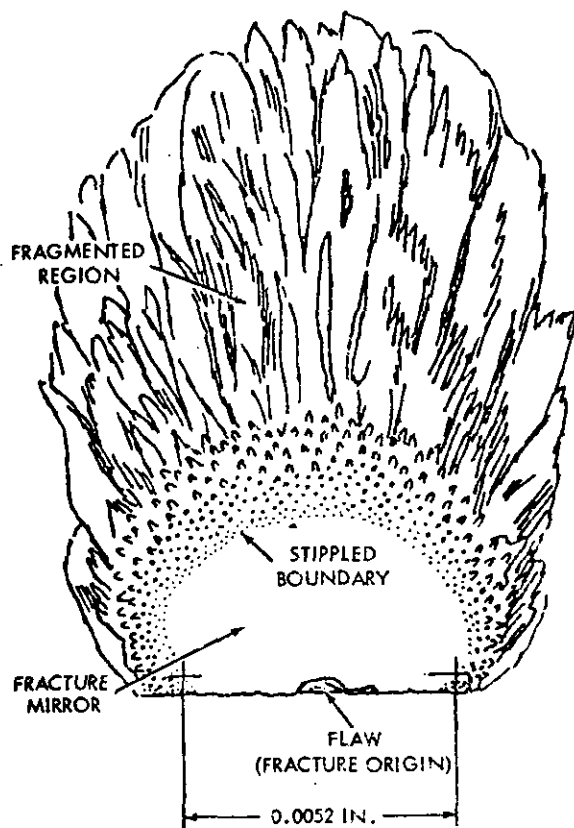
Experiments carried out to compare the effects of fatigue under static loading with those under cyclic loading indicate that for glass the fatigue limits are roughly the same in both cases, when based on the same value of maximum stress. When glass is subjected to a stress which will eventually break it, the flaw begins to enlarge at a slow rate. This enlargement proceeds at a more and more rapid rate, until the fracture velocity reaches the critical limit (at roughly one mile per second). (See Schardin [14].) At this velocity a transition occurs in the fracture process, which is usually visible on the fracture surface. The area representing the lower velocities is flat and smooth, and is called the fracture mirror. When the critical velocity is reached, the boundary of the crack surfaces becomes somewhat rough. In an outer boundary the crack hackled or fragmented. Figure 7, drawn from a photomicrograph, shows the fracture mirror and the two boundaries for a piece of glass broken under impact. The study of these mirrors is of practical importance, because the fracture stress can often be estimated from them.

c. *Prestressing.* The strength of glass articles can be increased by prestressing. The purpose of prestressing is not to increase the true breaking stress of the glass, but to redistribute the stresses so that a greater load may be applied before a breaking value can be reached in critical regions of the surfaces.

Tempering is the best known method of prestressing. The glass is raised to a temperature well above its annealing point and the surfaces are then chilled with a blast of air or other means. When the glass reaches room temperature, the surface layers will become highly stressed in compression, balanced by tensile stresses in the interior. When an external load is applied, its resulting tensile component must equal the residual surface compression of the glass before the resultant becomes tensile at all. Consequently, the strength of the article is increased by an amount roughly equal to the residual surface

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glass surface by larger ions. (See Chapter 2, Special Processes.) The thickness of the compression layer is generally much less than with tempering.

Figure 8 compares the distribution of residual stresses resulting from tempering and from chemical treatment.

d. Variance of Breaking Stresses. Figure 9 includes individual breaking stresses measured for sample groups of three glasses and one glass-ceramic body, plotted on a probability basis. These curves are representative, but it must not be inferred that other sample groups of the same materials will have identical characteristics. Furthermore, these data are for fairly high rates of loading, so that the stress duration corresponds to a time period of perhaps three to ten seconds. For longer durations, the stress values would have been correspondingly lower.

FIGURE 7. Fracture Surface Produced by Impact. Showing fracture flaw and surrounding it, the semi-circular fracture mirror, the stippled boundary, and the hackled or fragmented region beyond
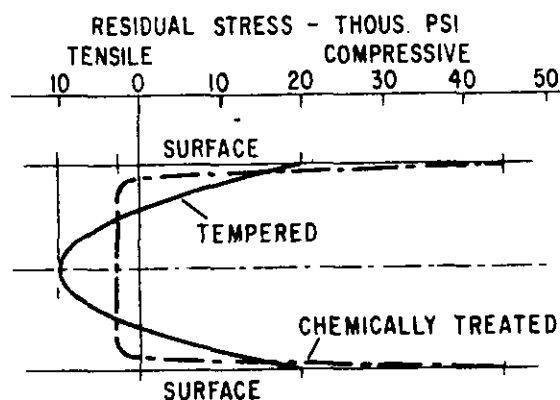
compression. This statement is oversimplified, but it gives an indication of the effects of prestressing. Curve B of Figure 6 shows that the relative effect of stress fatigue is greatly reduced by tempering.

Prestressing can be accomplished by chemical treatments, which replace small ions in the

FIGURE 8. Distribution of Residual Stresses across the Sections of Glasses, Tempered and Chemically Strengthened
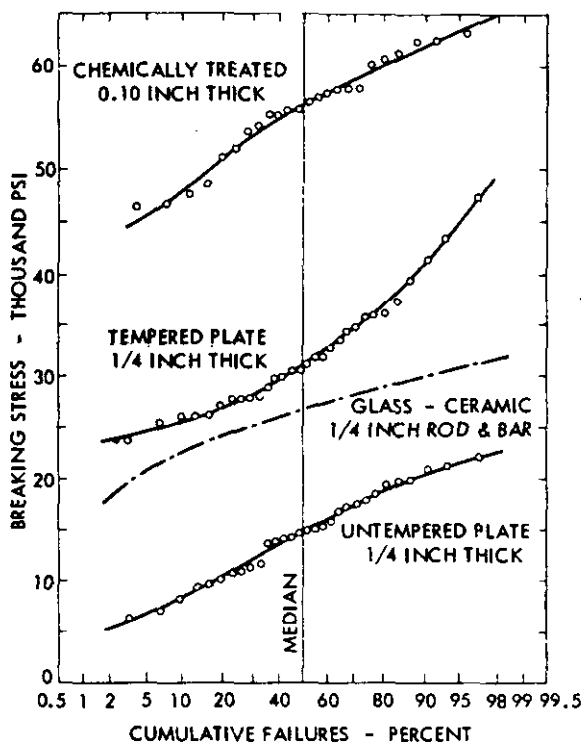
FIGURE 9. Individual Breaking Stresses for Groups of Glasses with Different Treatments and One Glass-Ceramic. Data plotted on a probability basis; collected by Shand, see reference [7]

Stress variations between the stronger and weaker members are greatest in the case of untempered glass. The median value is 14,500 psi, but two percent of the group broke at stresses of 5,000 psi, or 35 percent of the median value. When tempered, the median breaking stress was 31,000 psi, with two percent of the group breaking at 24,000 psi, or 77 percent of the median. This shows that tempering not only increases the strength of the article, but can also reduce variances.

For the chemically prestressed glass the median value was 56,000 psi, with the two percent stress 77 percent of the median.

The glass-ceramic, which was of the medium coefficient of expansion type, had a median stress of 27,000 psi, with two percent of the group breaking at 65 percent of this value.

The type of probability curve used in Figure 9 is useful in showing variances of strength among the members of a group tested. Other types of probability curves may also be used for this same purpose. In the correlation of scientific data, the average value and the standard deviation are commonly used to express these relationships. This procedure is not recommended for strength data on glass where the minimum values are of greatest interest. For skewed distribution curves, such as those for tempered plate and for glass-ceramic (Figure 9), the projection of stress values to two standard deviations (roughly three percent of the population) will result in errors which cannot be tolerated for the purposes of structural design.

e. Strength of Fibers (Reference [17]). It has already been noted that fibers drawn experimentally with unusual care will develop strengths greater than one million psi. Textile fibers drawn commercially under special conditions can attain strengths of more than one-half million psi, but for ordinary textile products mean fiber strengths for the glass listed as No. 10 in Tables I and IV may be 300,000 psi, or slightly more. With a special glass composition, fibers can be drawn which are more than one-third stronger than those of glass No. 10. Some deterioration of the fiber surfaces occurs in textile fabricating operations, so that strength values of resulting products must be reduced correspondingly. Values of fiber strengths after handling and fabricating have been reported as low as 150,000 psi, and even less.

f. Effect of Temperature. Temperature has its main effect on the amount of stress fatigue developed. In Figure 10, which includes the data of Vonnegut and Glathart [18], for temperatures from -187°C to +520°C, and load durations from 0.1 second to 100 seconds, the curves for the various temperatures seem to converge at a load duration where the stress fatigue is very small. At a temperature of -187°C, stress fatigue is barely appreciable. The maximum effect of stress fatigue occurs at 200°C, a temperature where water vapor is probably most active. At 520°C the effect of stress fatigue again decreases greatly. The breaking stresses of a

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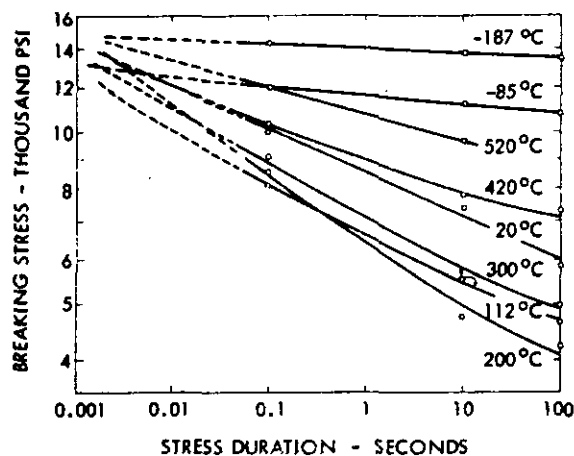
FIGURE 10. Breaking Stresses of Glass as a Function of Stress Duration at Different Temperatures. Data of Vonnegut and Glathart, see reference [18]

metal plates. Those made by Winkelmann and Schott, cited by Hovestadt [19], show that for a particular glass the breaking stress with the glass pressed between two plates of tin was 56,000 psi; with copper plates, 93,000 psi; and with hardened steel plates, 180,000 psi. The tin and copper plates were indented by the glass, which was apparently responsible for the lower breaking stresses. A similar effect was observed when the steel plates became roughened in use. Glasses of 17 different compositions were tested between steel plates. The mean values of breaking stress ranged between 86,000 and 180,000 psi, with an average of about 120,000 psi. These tests show clearly that conditions at the interface between the glass and metal have a pronounced effect on the value of compressive strength measured in this manner. If a gasket is inserted in the interface in order to equalize the stresses over the surface of the glass, the breaking stress may be reduced seriously because the lateral flow of the gasket will produce tensile stresses across the surface of the glass. Softer gaskets can even penetrate surface flaws in the
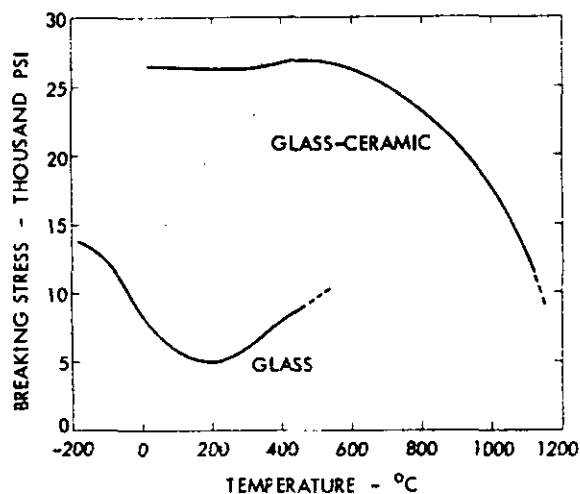
glass and of a glass-ceramic are shown as a function of temperature in Figure 11.

For conditions of sustained loading, the temperature of annealed glass must be held appreciably below the strain point, otherwise viscous flow will take place. Glassware prestressed by tempering or by chemical processing loses its residual stresses at lower temperatures, so that such a glass is restricted to temperatures about 200°C or even 250°C below the strain point. Within the operating ranges, temperature has much less effect on glassware's stress fatigue than that of annealed glass.

g. **Glass Under Compressive Loads.** The intrinsic strength of glass in compression is probably at least as great as it is in tension. When loaded in pure compression, the flaws tend to close so that nominal breaking stresses are much higher than when loaded in tension. However, a condition of pure compression is practically unattainable, and local components of tension cause premature failure, usually at the areas of load application.

Uniaxial compression tests have been made on glass by loading small cubes between two
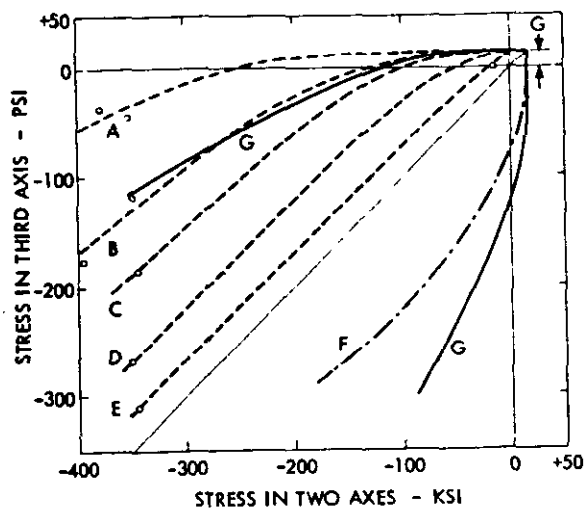
FIGURE 11. Breaking Stresses of Glass and Glass-Ceramic as a Function of Temperature for Short-Time Tests. Data for glass from Figure 10; for glass-ceramic, Coming Glass Works

FIGURE 12. Loci of Stress Components at Fracture for Glass Subjected to Triaxial Stress Conditions. Protection from fluid at interface: A, copper sheath; B, lead sheath; C, rubber sheath; D, neoprene sheath; E, no sheath; data of Bridgman, reference [20]. F, tungsten-carbide anvils with lead foil at interface; data of Cordell and Corll, reference [22]. G-G, theoretical curve, biaxial stresses

glass and produce cleaving forces which may split the body. This effect has been investigated by Bridgman [20] and others [21], in which glass has been subjected to triaxial compressive stresses. In two axes the stresses are equal, while in the third the stress is different. Data from such tests are few, but they are interpreted approximately in Figure 12. The dashed lines represent, as nearly as can be determined, the stress components needed for fracture. The stress G in the upper right-hand quadrant is the breaking stress of the glass in tension. Extensions of the G curves into the compressive quadrant represent the corresponding breaking stress under biaxial compression, derived analytically on the basis of certain assumed flaw orientations. Curves A to E show how the material in contact with the glass interface affects failure. Considering the case where the stress in the third

axis is zero, if a fluid is in contact with the glass (curve E), the breaking stress is less than 20,000 psi. Fluids penetrate the flaws readily. When the glass is protected from the fluid with a lead sheath (curve B), the breaking stress is increased to 120,000 psi. Using a copper sheath, with little tendency to penetrate the flaws (curve A), the breaking stress increases to about 250,000 psi.

Curve F represents the data of Cordell and Corll [22], who compressed the glass between tungsten carbide anvils with lead foil at the glass interface. When the lateral pressure was zero, with only that on the anvils acting, the breaking stress was 82,000 psi.

While these results are far from being precise, they demonstrate how different loading arrangements will influence failure under compressive loads. Because this type of failure actually results from tensile stress components acting across the interface, prestressing this surface will have beneficial effects, similar to those obtained when the glass is subjected to tensile stresses.

OPTICAL PROPERTIES

The optical use of glasses is not confined to the visible spectrum, so that its properties are important over a much wider range. In silicate glasses the range of transmission extends from approximately 0.2 microns to 5 microns. For certain silica-free glasses the range can be extended to about 15 microns.

The refractive index of a glass is a measure of its optical density, that is, the extent to which the velocity of the radiations is slowed down in comparison to air or vacuum. If the refractive index is 1.500, the velocity of the radiation in the glass is 1.000/1.500 = 0.67 that of its velocity in air.

Table IV lists the refractive indexes of some commercial glasses. The refractive index increases with the content of lead oxide. In a glass containing 82 percent of this oxide, the refractive index is 1.97.

The changes of refractive index with wavelength is called dispersion. This property is

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utilized in designing lens systems which are substantially free from chromatic aberration. The common method for indicating dispersion was developed by Abbe and his equation is called the ν (nu) value, or Abbe constant, where

$$\nu = \frac{n_D - 1}{n_F - n_C} . \qquad (4)$$

The letter n denotes the index of refraction, while the subscripts represent the wavelengths at which they were measured. F is the hydrogen emission line, 4,861 Å, C is the hydrogen emission line, 6,563 Å, and D is the sodium emission line, 5,893 Å.

18. Birefringence. Changes in the refractive index are commonly used to measure mechanical stress in glasses. If the stresses acting in two geometrical axes differ, then the refractive indexes in these axes for a light passing through the glass in the third axis will differ. The retardation of light in one axis with respect to the other axis is measured with an instrument called a polarimeter. The difference between the stress values in these two axes is expressed as follows:

$$\text{Stress difference (kg/cm}^2) = \frac{R}{t \times B} , \qquad (5)$$

where   R = the retardation (millimicrons),

   t = thickness of section (cm), and

   B = birefringence constant or stress optical coefficient

The values of B, expressed in $m\mu/cm$ per $kg/cm2$ are listed in Table IX. The specular reflection of light is produced by flat, smooth glass surfaces. The reflectance is a function of the refractive index, and for a single surface of transparent glass is usually about four percent. For two surfaces of a plate it will be double this value, or about eight percent. If the surface is roughened, either by rolled patterns or by grinding, the reflected light will be diffused or scattered. In opal glasses, light is diffused within the body of the glass, so that the amount of diffused light reflected may be much greater than for transparent glasses.

TABLE IX. BIREFRINGENCE CONSTANTS OR STRESS OPTICAL COEFFICIENTS

Type of Glass	$B \dfrac{(m\mu \quad x \quad cm)}{kg}$
Silica glass	3.40
96% Silica glass	3.60
Soda-Lime	2.40 - 2.60
Lead-Alkali glass	
20% PbO	2.50 - 2.70
75% PbO	0
80% PbO	-1.00
Borosilicate (low expansion)	3.8
Aluminosilicate	2.6
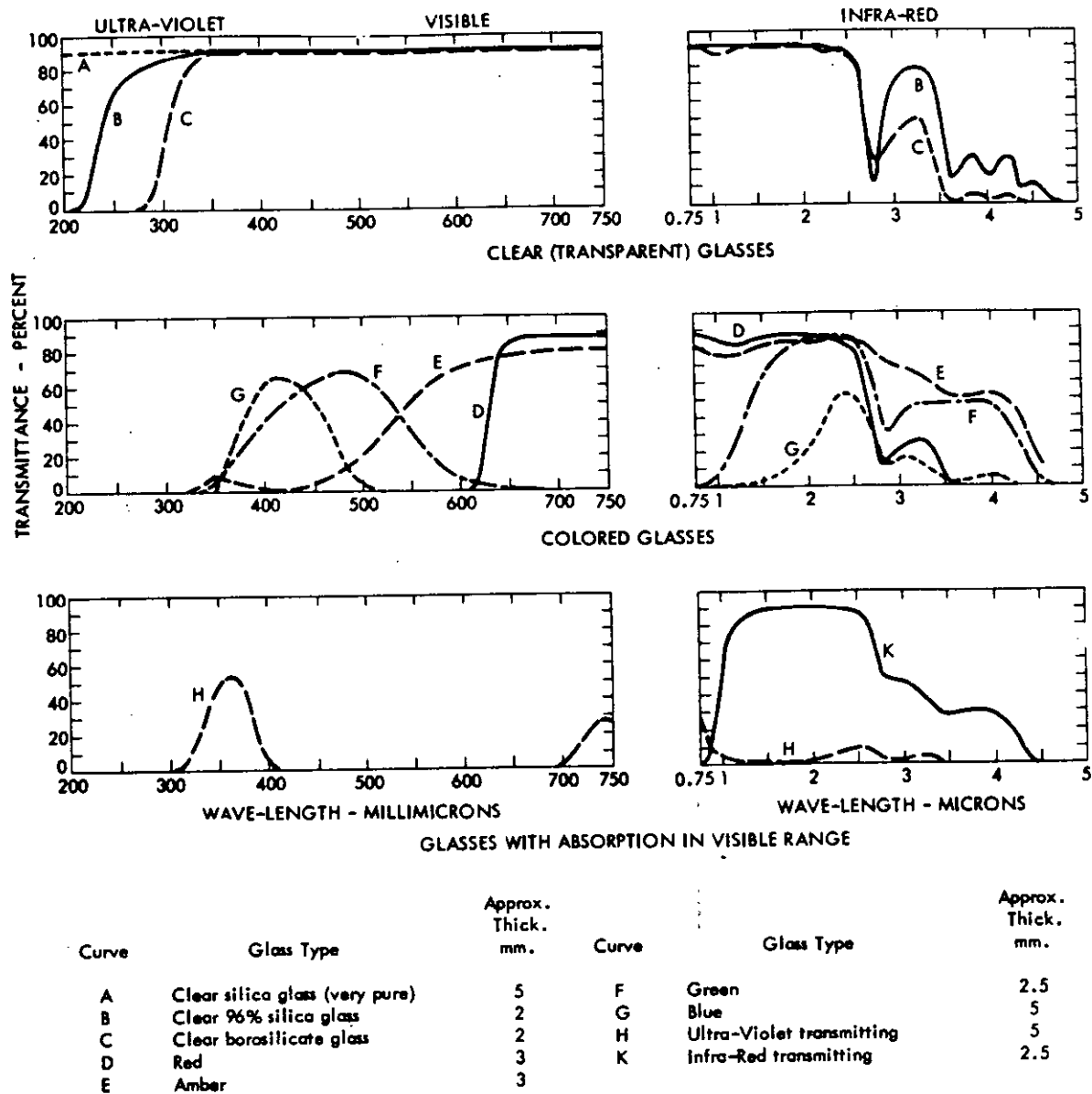
FIGURE 13. Curves of Transmittance versus Wavelength for Selected Filter Glasses. Data from Corning Glass Works

Reflectance can be reduced greatly by non-reflecting coatings, and can be increased by thin metallic films. The metallic films which are commonly used are those which reflect most highly in the infrared part of the spectrum.

19. Transmittance. Figure 13 illustrates the transmission characteristics versus wavelength of different types of glasses. The visible spectrum extends from 400 to 750 millimicrons wavelength. After subtracting the reflectance loss,

the absorption of light by glass is an exponential function of thickness, consequently the transmission spectrum of clear glasses can be extended by using thinner sections. For colored glasses, the color density can be increased by using thicker sections.

Glasses which transmit only in the ultraviolet or infrared parts of the spectrum have military uses, for example, in signaling and in the guidance of rockets (additional information on the military uses of glass may be found in Chapter 5).

Clear glasses can be discolored by x- and gamma rays. Various photosensitive glasses can develop color after exposure to light, to ultraviolet radiations, and to x-rays. In some cases the latent image produced must be developed by the application of heat.

ELECTRICAL PROPERTIES

20. Volume and Surface Conductivity. Electrical conductivity is the result of ionic mobility, particularly that of certain of the alkali ions (Li, Na, and K). This mobility increases rapidly with temperature, and conversely, the volume resistivity decreases rapidly with temperature. Figure 14 shows the relation of the logarithm of resistivity to temperature of common commercial glasses between 100 and 600°C. At room temperature electrolysis presents measurement problems. In general, glasses are good electrical insulators; molten glass, however, is a relatively good conductor of electricity, so that glass can be heated by electric currents. Electrical resistivity, and in fact, all electrical properties, are particularly responsive to the previous thermal treatment of the material.

Volume resistivities at 250°C and 350°C are included in Table IV.

The surface conductivity of glasses is influenced greatly by water vapor, and thus by the relative humidity of the atmosphere. With low relative humidities, the surface resistivities usually range from 10^{14} to 10^{16} ohms per square.*
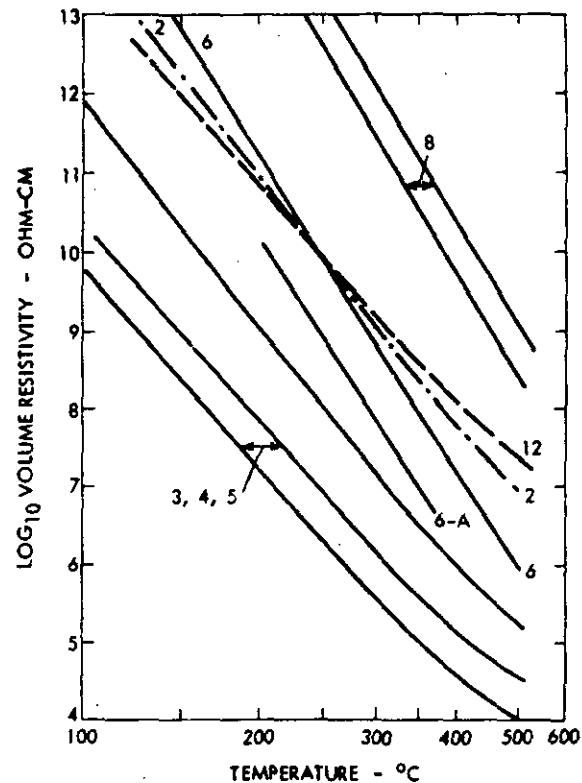
FIGURE 14. **Volume Resistivity of Commercial Glasses versus Temperature. Numbers are those of Tables I and IV**

For humidities of 90 percent, these values drop to 10^7 to 10^{11} ohms per square, but can be increased by treating the surfaces with silicones or other materials.

21. Dielectric Quantities. An electric field set up in a body represents energy. If a considerable portion of this energy is recoverable, the body is called a dielectric. The ratio of the energy lost as heat to that recovered is called the dielectric dissipation factor, and is sometimes expressed as the tangent of the loss angle, or tan δ.

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*The resistivity of a film measured between opposite edges of any square will be the same regardless of its dimensions. Consequently, surface resistivity is expressed in ohms per square.
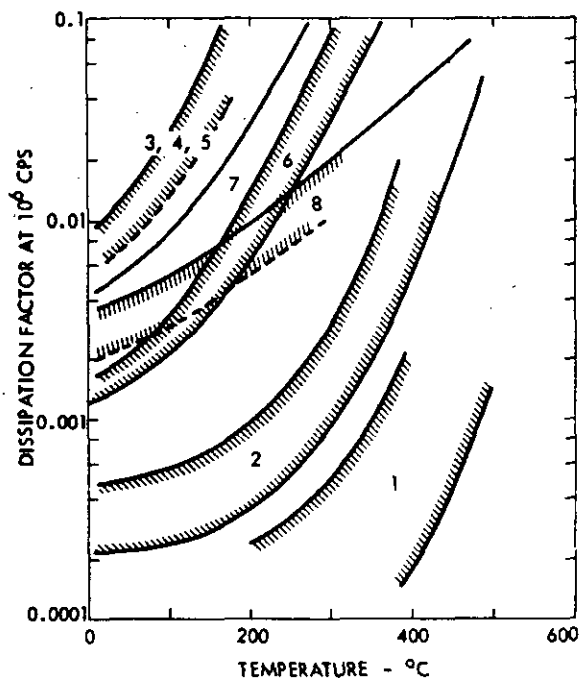
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FIGURE 15. Dissipation Factor versus Temperature at 10^6 CPS for Commercial Glasses. Numbers are those of Tables I and IV

The energy of the electric field is not the same for all materials. The ratio of this energy to that in a vacuum is called the dielectric constant, e', of the material. The relative energy loss is then proportional to the product of the dielectric dissipation factor and the dielectric constant, or, $e'\tan\delta$. These two quantities are listed in Table IV for a number of glasses for a frequency of one mc, and a temperature of 20°C. For other temperatures, the variation of dissipation factors for these glasses is shown in Figure 15. Note that for the silica glasses, Curves 1 and 2, there is a wide spread of values. This is caused mainly by the presence of tiny amounts of constituents other than silica, Na_2O in particular.

22. Dielectric Strength. Dielectric breakdown may occur when the voltage gradient exceeds the intrinsic dielectric strength of the material, or when the glass becomes partially conducting because its temperature is raised by dielectric

losses. The former type of breakdown is called "electronic," and the latter type, "thermal."

Electronic breakdown may occur when very thin sections are subjected to momentary voltages. Values of dielectric strength of glass as high as 9×10^6 volts per cm have been measured in this way. Under less ideal conditions, the voltage gradients through the specimen will not be uniform, so that the average gradient at breakdown may be much lower.

As the duration of the electrical stress is increased, local heating develops within the specimen so that the mechanism involves thermal conditions. When alternating voltages are used, the heat generated in the specimen increases greatly and the apparent dielectric
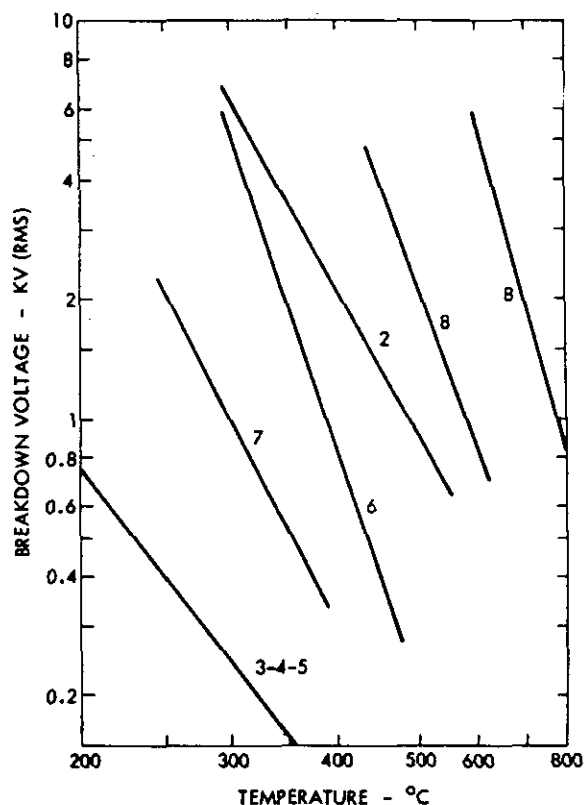

FIGURE 16. Dielectric Breakdown of Commercial Glasses versus Temperature. One-minute breakdown for 2-mm thickness at 60 cps; numbers are those of Tables I and IV

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strength decreases correspondingly. In a series of tests on glass specimens 0.030-inch thick, the data obtained were as follows:

60 cps, 500,000 rms volts/cm,

2 mc, 35,000 rms volts/cm,

100 mc, 8,300 rms volts/cm.

When a breakdown is of thermal origin the breakdown voltage tends to increase at a rate not greater than the one-half power of the thickness, so that the expression of dielectric strength in terms of volts/cm or volts/mil is deceptive.

The effect of ambient temperature on breakdown voltage is shown for a number of types of glasses in Figure 16.

23. Absorption of High-Energy Radiations. An atom of any element will absorb x- and gamma rays to the same extent, regardless of whether it is in a solid, such as a metal, in a gas, or combined with other atoms in a chemical compound. The relative absorption of various atoms and compounds is called a mass-absorption coefficient, μ/ρ, with dimensions of square centimeters per gram (and where μ is a linear coefficient with dimensions cm^{-1}). This coefficient is a function of the characteristics of the radiation (electron volts or wavelength), as well as of the material. If the chemical composition of a glass is known, the absorption of each constituent can be computed separately and then combined to give the absorption of the glass. (Additional information, together with the tabulated values of the mass-absorption coefficients of some common glass constituents, will be found in Reference [6].)

Lead is particularly effective in absorbing these radiations, so that the absorption characteristics of glass and other materials are frequently given in terms of their "lead equivalents." For a glass containing some 76 percent lead atoms, the coefficient μ may be from 43 to 60 percent of that of metallic lead, depending upon the energy of the radiations.

After prolonged exposure to high-energy radiations, some glasses will darken. In the case of high-lead glasses, this darkening will fade during periods of rest at room temperature.

Glasses with lower lead content have been developed which are highly resistant to darkening.

24. Chemical Durability. All of the general-purpose commercial glasses which are noted here are stable, but in some, such as borate and phosphate glasses, chemical durability may have to be disregarded for other special properties.

Water and acids have negligible effect on these glasses at temperatures up to $100^{\circ}C$. Hydrofluoric acid is an exception, as it will attack the silica content at all temperatures. Strong bases, such as NaOH and KOH, will attack glass appreciably at elevated temperatures, even in 5 percent solutions. A 5 percent solution Na_2CO_3 will also attack glass at elevated temperatures, but at a lower rate.

Table X includes data for chemical attack under arbitrary test conditions which permit different compositions to be compared. The loss of weight of the specimen is determined and divided by the surface area exposed to the reagent. These results indicate that the 96% silica and the borosilicate glasses are exceptionally durable in acids, but that the aluminosilicate glass is much less so. The aluminosilicate glass has unusual resistance to the attack of 5% NaOH. Glasses which are exceptionally high in lead oxide content, as well as certain of the borosilicate glasses, are not resistant to attack by acids.

The rate of chemical attack is not necessarily constant with time; consequently, care must be used in extrapolating the results of Table X for longer periods of time.

The attack on glass surfaces by atmospheric moisture is referred to as "weathering." Glasses of lower chemical durability are adversely affected by such weathering. In the case of more stable glasses containing appreciable amounts of alkali, such as the soda-lime glasses, the action of weathering is more complex. The moisture leaches soda from the surface, which may increase the alkalinity of the moisture to a degree which permits it to attack the surface and cause fogging and even pitting. In general, glass should not be stored in damp places, and there are various treatments which can be carried out to reduce the effects of weathering.

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TABLE X. CHEMICAL ATTACK ON GLASSES

No.*	Type of Glass	Weight Loss (mg per cm^2)		
		5% HCl (24 hrs., 100°C)	5% NaOH (6 hrs., 99°C)	N/50 Na_2CO_3 (6 hrs., 100°C)
2	96% Silica	0.0004	0.9	0.07
4	Soda-Lime (plate)	–	0.8	0.18
5	Soda-Lime (containers)	0.02	0.8	0.20
–	Soda-Lime (lamp bulb)	0.02	1.1	0.25
6	Lead-Alkali (electrical)	0.03	1.6	0.25
7	Borosilicate (low expansion)	0.0045	1.4	0.12
8	Aluminosilicate	0.35	0.35	0.17

* These numbers correspond to the glasses of Table IV

Chapter 4
Technological Principles

ANNEALING AND TEMPERING

The word "anneal" has been defined by ASTM in the following manner. . . "to prevent or remove objectionable stresses in glassware by controlled cooling from a suitable temperature." The terms annealing and fine annealing are also used for the processes of slow cooling for the purpose of stabilizing the structure of glass, and thus to prevent changes of properties with time. This applies particularly to optical glasses where the constancy of the refractive index is important, and to fever thermometers where changes of glass dimensions affect calibration. The present discussion is confined to the subject of residual stresses.

If glassware is cooled haphazardly immediately after being formed, the distribution of the residual stresses will be uncontrolled so that breakage may result when the ware reaches room temperature. The procedure used for both annealing and tempering is to bring the glass to a uniform temperature above the transformation range, and then to cool it under conditions which control the distribution of its residual stresses at room temperature. If the cooling conditions result in residual stresses which are relatively low, the process is called annealing, and if relatively high, it is called tempering. There is no clear line of distinction between the two.

For some purposes a stress level of 500 psi on the glass surface is considered to represent satisfactory commercial annealing, but this limit changes with the type of ware and service requirements. In the case of window glass, the compressive stress on the surface is normally not less than 700 psi, and for certain classes of tubing the compressive stress on the outer surface may exceed 1,000 psi. These stresses add

strength to the product, but when increased appreciably result in difficulties in cutting by scoring methods.

Plate glass is considered to be fully tempered when the compressive stresses at the surface exceed 13,000 psi, and lightly tempered when the stresses are less than 9,000 psi, but for some classes of ware these limits may be much lower, even 5,000 to 2,500 psi. Under some circumstances, it may be desirable to reduce the residual tensile stresses at the midsection to a value where cracks are not self-propagating. This may reduce the tensile stress limit to about 3,000 psi.

Residual stresses in a particular piece of glass are established by the rate at which it is cooled through the transformation range, which is conventionally considered to extend from the annealing point to the strain point. This cooling rate sets up a temperature differential between the interior of the glass and the surface, with consequent differences of specific volume. At the annealing point, these differences of volume can adjust themselves by viscous deformation. Below the strain point, these volumetric differences still exist, but are not permanently set. When the temperature of the glass again becomes uniform, the permanent deformations can be compensated only by elastic deformation (which represents stresses).

When a glass plate is being cooled at a constant rate*, the temperature difference ΔT between the central axis and the surface is

$$\Delta T = \frac{a^2 R}{8K} .$$

(6)

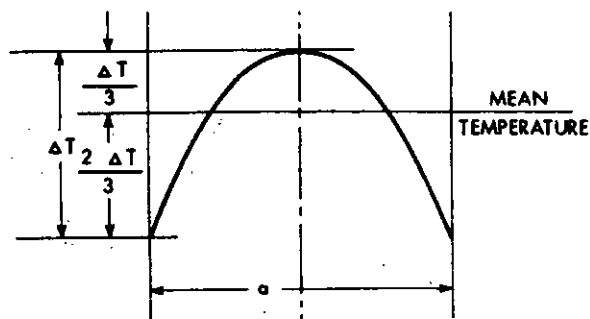*The analysis is given a more complete form in Reference [6].

FIGURE 17. Temperature Distribution through a Section of Glass Being Cooled at a Constant Rate; Stabilized Gradient

With a temperature distribution across a section of glass as shown in Figure 17, the resultant residual tensile stress after temperature equalization can be expressed as

$$\sigma_t = \frac{E \alpha a^2 R}{10K (1 - \nu)} \qquad (7)$$

The compressive stress at the surface will be approximately double this value.

When common values are substituted for the various factors, the equation may be simplified to

$$\sigma_t = 10^9 \alpha a^2 R \ ,$$

or

$$R = \frac{\sigma_t}{(\alpha \times 10^9) a^2} \ , \qquad (8)$$

where ΔT = temperature difference across a section ($^\circ$C)

a = section thickness in inches,

R = cooling rate ($^\circ$C per second),

K = thermal diffusivity of the glass = $\dfrac{\text{thermal conductivity}}{\text{density} \times \text{true specific heat}}$,

(The value of K is roughly 0.0013 sq. in./sec.)

α = coefficient of expansion of the glass below the strain point, and

σ_t = central tensile stress (psi).

From Equation (8) it is noted that the cooling rate is inversely proportional to the coefficient of expansion of the glass, and inversely proportional to the square of its thickness.

In actually carrying out the annealing operation, the temperature of the glass in the furnace is usually raised to a few degrees above its annealing point. The cooling rate computed for the desired stress is maintained to some temperature below the strain point, after which the cooling rate may be increased. For hollow ware the cooling effect at the internal surfaces is usually very low, so that the effective thickness is assumed to be nearly double its actual thickness.
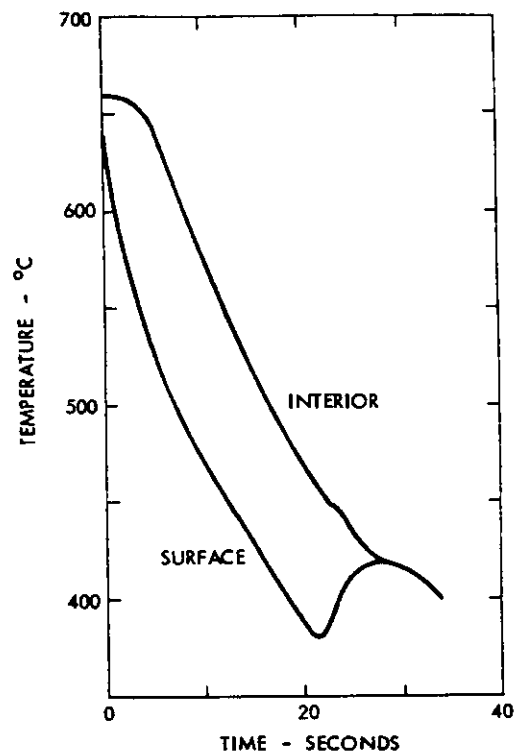

FIGURE 18. Temperature-Time Curves for Surface and Interior of Plate Glass 0.236 Inch Thick, During Tempering Operation. Data, Grove et al., see reference [23]

In the case of tempering, the method of computation is reversed. Assuming a value of σ_t for the internal residual stress, the required rate of cooling, R, may be determined from Equation (8). Knowing R, the temperature difference, ΔT, may be computed from Equation (6). The temperature of the glass in the furnace should be raised to a value at least ΔT above the annealing point of the glass.

There are several factors which limit the residual stresses attainable. If a maximum cooling rate, R, is established for the process, then the maximum stress, σ_t, is determined by the coefficient of expansion and by the thickness of the glass. For thicker sections there is also a limit to the temperature difference, ΔT, because viscous distortion of the glass becomes serious near the softening point. Figure 18 shows experimental cooling curves taken for the interior and for the surface of a glass plate while undergoing tempering [23]. The main cooling rate at the surface is roughly 37°C per sec, or 2,200°C per minute. Other data on tempering have indicated materially higher rates of cooling.

THERMAL STRESSES

When one part or component of a structure, when attempting to expand or contract in response to a temperature change, is restrained by a second part or component which does not change dimensions equally, thermal stresses are set up within the structure. These stresses can originate in two ways; first, in a homogeneous structure they may be caused by temperature differences throughout the structure; second, in a structure which is not homogeneous (consisting of components with different properties), they may be caused when the temperature, uniform over the structure, differs from one value where no stresses occur. In many practical cases it is found that these two types of thermal stresses will be combined.

Stresses of the first kind in homogeneous structures sometimes result from steady-state conditions, as in the case where a temperature drop occurs through the section of a glass wall or plate. If the gradient through this section is uniform the thermal stresses can be expressed:

$$\sigma_T = \frac{E\alpha\,\Delta T}{2(1-\nu)}, \qquad (9)$$

where σ_T = surface stresses (compressive on the hot side and tensile on the cold side),

ΔT = temperature difference,

α = thermal expansion coefficient of the glass,

E = modulus of elasticity of the glass, and

ν = Poisson's ratio.

Equation (9) is based on the assumption that the plate or wall is restrained so that it cannot warp. If warpage occurs the stresses can be much lower than indicated by the equation. The wall of a cylinder is restrained, so that the equation will apply.

If one surface of the plate is suddenly heated or cooled, the temperature distribution and the stresses will pass through a transient phase before a steady-state is reached. The temperature distribution at any moment is a function of the thermal diffusivity of the glass, $K = k/\rho c_p$, or the thermal conductivity divided by the product of the density and the true specific heat. Values of K may vary from 0.0026 cm2/sec for high-lead glasses to 0.009 for silica glass. Once the temperature distribution is determined, the stresses can be computed with the special use of Equation (9). The computation of these transient stresses is somewhat involved so that other literature should be consulted for details [4] and [6].

A typical example of thermal stresses developed in structures which are not homogeneous is found in glass-glass and glass-metal seals. The two seal components are joined or sealed at a specific temperature. If the thermal expansion characteristics of the two components are not identical, stresses will develop at any other temperature, with opposing forces in the structure.

Much effort has been devoted to the development of glasses which can be sealed together at elevated temperatures and then cooled to room temperature without producing excessive thermal

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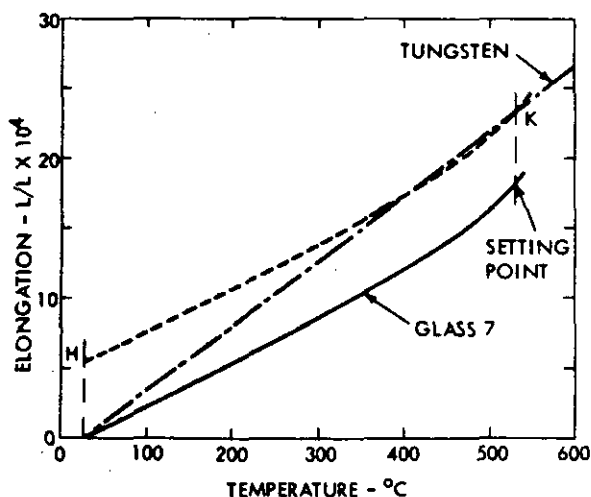
FIGURE 19. Glass to Metal Sealing Properties

stresses. In Figure 5, curves 3-5, 6, and 9 are for glasses of a compatible group which can be sealed at temperatures over a range extending from 350°C to nearly 500°C. Glass 9 was developed specifically for the purpose of sealing the other glasses together at relatively low temperatures.

Metals and alloys have been developed which match the elongations with temperature of the various groups of glasses used for sealing purposes. Figure 19 includes the elongation curves of a sealing metal and a glass. The two materials will seal together at the setting point of the glass, usually 0° to 10°C above its strain point. When the curve for glass 7 is superposed on that of tungsten so that they coincide at the setting point, the difference in elongation at room temperature, 0H, will determine the stresses set up. Other factors include the size and geometrical arrangement of the seal structure. Additional information has been given by Partridge [24].

STRENGTH TESTING AND MEASUREMENT

Methods of testing glass for strength are essentially the same as for other materials, but procedures are modified in some respects, because of the brittle characteristics of glass. A number of studies have been made of this subject and the National Bureau of Standards is now engaged in another study [25].

Wide variations of breaking stress within the same group of samples (already mentioned in Chapter 3 in Paragraph 17, Strength) may require minor modifications in test procedure. In particular, it is often essential to know, with some assurance, the breaking stresses of the weaker members of the population. For those materials with small variances, the average breaking stress and the standard deviation may give a fair approximation of the lower breaking stresses. For glass, with its greater variances, this statistical procedure can result in serious inaccuracies. Figure 20 shows two distribution curves, A and B, breaking stresses for glass samples. Both types of curves actually occur experimentally. For both curves the average values are identical, and also the standard deviations; however, when these quantities are used to extrapolate breaking stresses for a level of minus two standard deviations (-2σ), the result will be 26 percent high for curve B, and 14 percent low for curve A. If this procedure is carried out to -3σ, the inaccuracies will be much greater. It is also found
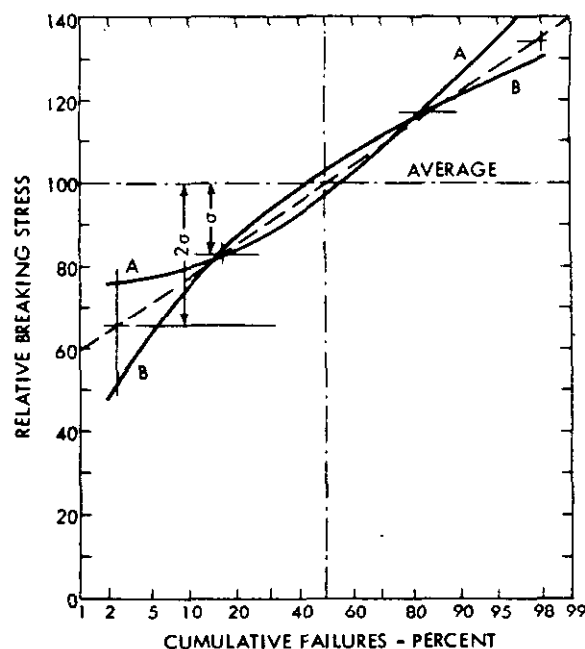
FIGURE 20. Effect of Use of Standard Deviations to Determine Low Breaking Stresses

that the distribution curves for glass are often bimodal so that even when compensation is made for skewness, as with the Weibull statistical method,* the inaccuracies persist. Consequently, it is essential to use samples with a sufficient number of specimens so that extrapolation is not required. In order to find the breaking stress at a level of two percent of a population, the sample should consist of 50 specimens.

The distribution of flaws of various sizes over a surface means that the larger the surface under stress, the greater will be the probability of the presence of a serious flaw, and the lower the breaking stress. Consequently, the stressed area becomes of particular importance when the test specimen has only a small fraction of the area of the product under consideration. An example of this is the use of a small bar or strip to investigate the strength properties of a large plate. Statistical methods can be applied to compensate for this difference if adequate data are available. Experimental data on the area effect are included under Paragraph b, Flexure Tests.

The treatment of the glass prior to testing and the conditions under which the test is carried out have a material effect on the value of the breaking stress. Surfaces are sometimes abraded to simulate damage which may occur in service. By reducing variances this treatment can also permit smaller samples to be tested, but unless the severity of this abrasion is well correlated with service which the particular product will encounter, the test results can lead to conclusions regarding suitability which are unjustified. Damaged surfaces can be repaired by polishing operations of various kinds. Heat treatment which does not develop residual stresses can either strengthen or weaken glass (Cornelissen and Zijlstra [13]). In other studies a sample of damaged glass broke at a mean value of 5,500 psi. After heating the glass for one hour at 400°C (5° below its strain point), and then cooling it to room temperature, the corresponding breaking stress was 7,600 psi, an increase of nearly 40 percent.

The comment is made in Reference [25] that when a fracture originates under a covering of masking tape, the breaking stress is apparently higher than when no tape is used. Some other observations indicated no significant difference in strength if the tape is applied to the glass within a period of minutes before it is broken.
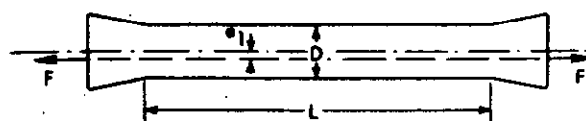
The time factor involved in strength tests is important, because of static fatigue or delayed fracture. To place this time factor on a common basis for various test conditions, it should be expressed in terms of the time duration of the breaking stress. For convenience in testing, the load is usually raised continuously at a constant rate. The effective duration of the breaking load can usually be taken as the time interval required for the final 10 percent increase prior to fracture. For research purposes, and also for the measurement of fatigue limits, different values of fixed load may be applied to each of a number of groups and the time required for the fracture of each specimen recorded. The median member is taken to represent the group. In a third method, a load is applied to a specimen for a definite period of time. If fracture does not occur, the load is increased (usually about 10 percent), and the cycle is repeated. The stress applied at failure and the time period established for the test series are recorded for each specimen.

a. Tensile Tests. The tensile test which is used most frequently for other materials is not readily adaptable to glass. Not only are the ends of tensile specimens difficult to grip, but clamping weakens the ends and tends to cause premature failure. The ends may be enlarged to simplify the holding of the specimens, but this solution is not usually practicable. Even when tensile specimens are carefully aligned there will be the effects of eccentric loading, which often leads to serious bending stresses. Simple computations indicate that the length of the specimen should be at least 30 times its diameter, in order to reduce the bending components to low values. Fibers are usually tested in tension.

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*The Weibull and other statistical methods are noted by Duckworth and Rudnick [16], [16a], and [16b], and by Kingery [4].

$$\sigma_B = \sigma_T 8 \frac{e_1}{D} c^1 \qquad (11)$$

$$c^1 = 1 - \cfrac{1}{1 + \frac{3}{16} \frac{E}{\sigma_T} \left(\frac{D}{L}\right)^2} \qquad (12)$$

σ_B = MAX. BENDING COMPONENT OF STRESS

σ_T = TENSILE COMPONENT OF STRESS

E = ELASTIC MODULUS

e_1 = INITIAL ECCENTRICITY OF LOADING

**FIGURE 21. Effect of Eccentric Loading on Bending Stress Components in Brittle Bodies**

Figure 21 shows the relationship between the eccentricity of loading of a tensile specimen and the bending moment produced. The equations show that as the length of the specimen is increased, its flexure will decrease the eccentricity, so that the bending component will be reduced correspondingly. When the ratio L/D is equal to 30 or more, the effect of eccentricity is no longer serious.

b. Flexure Tests. Flexure specimens require no end gripping, so that this test is widely used for glass. Rods and bars or strips are loaded in simple uniaxial flexure, but plate specimens can be subjected to more complex conditions involving biaxial stresses.

One standard specification (ASTM Desig. C158), for the simple flexure testing of glass rods and strips, was established for the comparison of certain glass products following manufacture. The procedures set up are somewhat arbitrary, so that the values of breaking stress measured in this way may differ materially from corresponding results obtained from flexure methods recognized as being more satisfactory. As a consequence, this specification is generally modified when applied to flexure testing for other purposes. Referring to Figure 22, four-point loading (sketch B) is substituted for three-point loading (sketch A). In this manner a much

larger surface of the specimen can be subjected to the maximum moment, and thus to the maximum stress. Curve C shows the actual breaking stress as a function of the stressed area. A comparison of curves C and D shows that the fictitious breaking stress, computed on the basis of the maximum moment, can result in a value materially higher than the actual breaking stress. ASTM Design. C158 makes no correction for this discrepancy. The results shown in Figure 22 apply only to a specific population; the results of samples from another population might be somewhat different.

The simple flexure tests is often used to determine the strength of flat glass (plate or sheet) which has been cut into strips for this purpose. The edges of the strips are weakened by the cutting operation so that some of the fractures, sometimes more than one-half, will originate at these edges. Results obtained from groups of these specimens do not represent th.
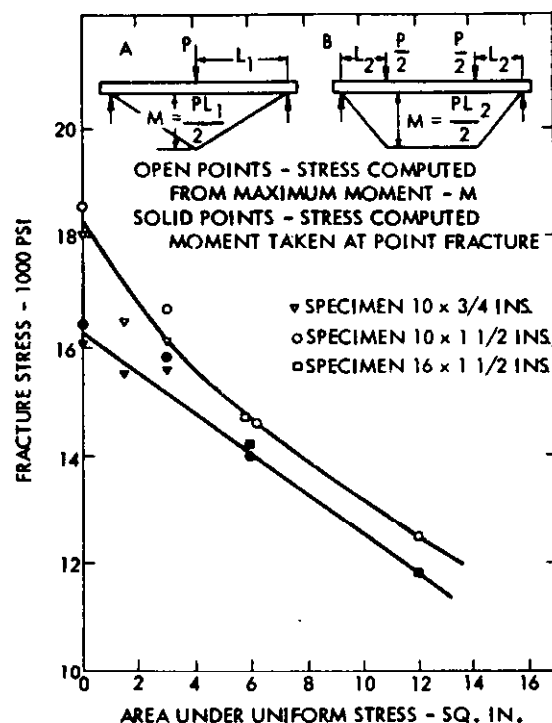
FIGURE 22. Effect of Stressed Area on Breaking Stress, and of Using Maximum Bending Moment in Computing Stress. Kerper et al. [29]
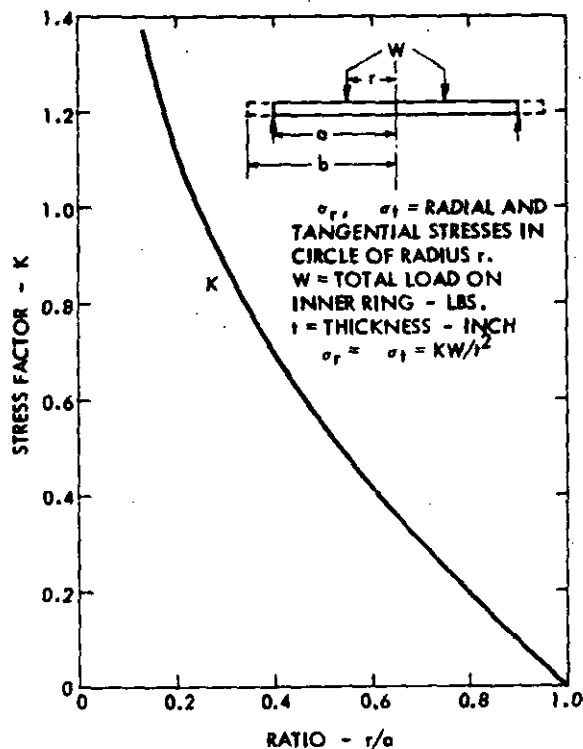
FIGURE 23. Method for Computing Bending Stresses in the Concentric-Ring Test. Applicable only when the central deflection does not exceed t/2, and when the ratio b/a does not exceed 1.05. Poisson ratio = 0.22

true strength of the plate or sheet. This error can be reduced materially by polishing the edges of the glass. For other types of tests it is sometimes practicable to abrade the surface so that it becomes weaker than the edges.

c. *Plate Flexure Tests.* The problem of edge breaks mentioned previously can be overcome by using plate specimens rather than strips, so that regions of high stress can be well removed from the edges. The concentric ring test is most commonly used for this purpose. The specimen is supported by one circular ring and loaded with a second ring which is concentric with the support and perhaps only one-half its diameter. Elementary stress analysis shows that the stress is uniform and biaxial (equal in all axes) over the

entire area of the inner ring. A method of computing these stresses is shown in Figure 23. Other advantages of this test include the ability of subjecting a relatively large area to the maximum stress, and the biaxial stress condition which renders all flaws equally vulnerable, regardless of their orientations.

The method also has its disadvantages. The specimen should be circular, with essentially no overhang beyond the support ring. If a square specimen is used for greater convenience the simple stress formula is no longer suitable, and the stress distribution over the area of the inner circle is no longer uniform. A relatively satisfactory compromise can be effected by using a specimen cut in the form of an octagon. The results of some initial studies of this concentric ring test are included in References [25] and [26]. These indicate that stresses cannot be computed from the load with suitable precision when the specimen departs from the desired shape; even with circular specimens, the correlation between stresses computed from the load and values measured with strain gages was not entirely satisfactory. Further extension of these studies may clarify this matter. Other experience with this test has shown that the determination of the breaking stress from the markings on the fracture surface can give satisfactory results.

An unusual type of plate flexure is required in specification MIL-G-2697, for tempered portlights (see Figure 24). The circular plate is supported at two places on the circumference, diametrically opposite, while the load is applied at two similar places on the opposite surface, but on an axis oriented at right angles to the supporting axis.

The arrangement used in this test is illustrated in the sketch of Figure 24. The plates tested were of annealed glass, six inches in diameter, with thicknesses from 0.065 to 0.24 inch. When loaded in the testing fixture, the breaks occurred in the positions indicated in the sketch. The breaking stresses were determined from measurements of the fracture mirrors. The slope of the curve indicates that the load required to develop a certain stress increases with the square of the plate thickness.

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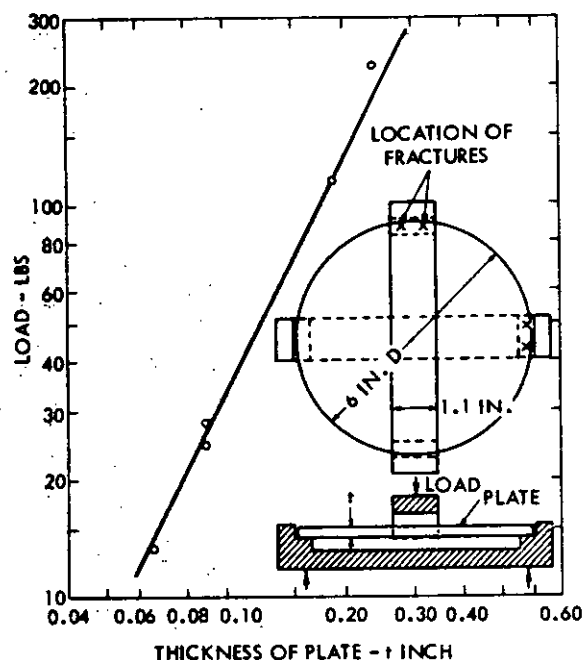
FIGURE 24. Load to Develop Bending Stress in Rim of 6000 PSI as a Function of Plate Thickness. Stresses determined from fracture mirrors

d. Torsion Tests. This type of test is seldom required. When the specimen is in the form of a rod, difficulty is experienced in gripping the ends. Torsion tests can be made on specimens in the form of a spiral spring, which is compressed or stretched until it fails.

e. Compression Tests. No procedures have been established for making compression tests of glass, nor is there any agreement on how the results of various types of compression tests should be interpreted. It is recognized that the nominal compressive strength of glass is merely a measure of the presence of tensile components which may be highly local in their extent.

Several methods can be used for making compression tests, depending upon the requirements. A steel ball pressed against a glass surface will show the effects of local pressure concentrations. Circular fractures develop around the contact boundary where the stress becomes tensile. For simple geometrical forms, the values of this breaking stress can be computed from the

Hertzian equations for contact stresses (Reference [27], p. 321). The precision of these equations as applied to glass has been questioned.

A glass block or short column can be compressed between two metal plates. Failures are usually caused by tensile components acting across the interface surface of the glass (as mentioned in Chapter 3, under Strength). Breaking stresses obtained in this manner are nominal, and tend to vary greatly with differences in test conditions and procedures. Attempts have been made to reduce the magnitude of the secondary tensile stress components by a careful adjustment of the elastic properties of the glass and the metal plates. Nominal breaking stresses can be increased materially in this way, but they are still far from representing a true compressive strength of the glass.

Tests such as those described in References [29], [21], and [22], have been used to measure breaking stresses of glass subjected to multiaxial compressive loads. Figure 12 shows how greatly the results can be affected by differences in test conditions. These methods have not been studied to a sufficient extent to understand the factors involved. Engineering tests of glass under multiaxial compression have been made on hollow glass hemispheres subjected to external hydrostatic pressures. The results of these tests also show wide variances, and that the glass is weakened seriously by the hemispherical joint. Various means have been tried in order to reduce these effects, either by special shaping of the joint, or by prestressing the glass in this region. Such measures have met with only partial success.

f. Impact Tests. Standard impact tests of the Charpy or Izod types are used on many engineering materials to measure a property or characteristic associated with the material. Such tests are also used to detect increasing brittleness as the temperature is lowered. When applied to brittle bodies, such as glass, these standard tests furnish no information which is different from that obtained from static strength tests. If suitable procedures are neglected, the data may not even represent the impact resistance of the specimen. Elementary theory indicates that impact resistance should correspond with the
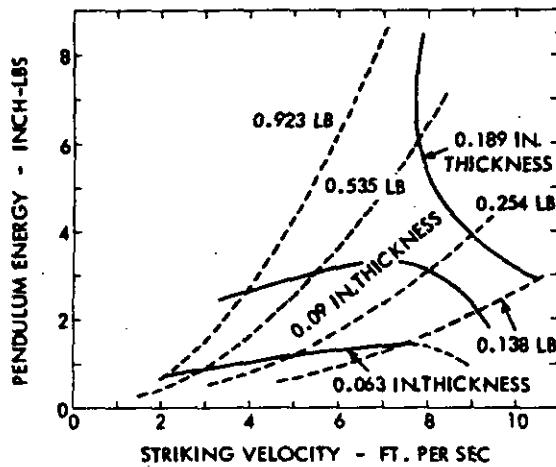
FIGURE 25. Mean Impact Energy versus Striking
Velocity for Impact Fracture of
Sheet Glass. Unsupported diameter
of specimen 1-7/8 inches. No
overswing of pendulum. Weight
figures are those of pendulum. Data
from Shand, Reference [29]

elastic energy stored in the specimen at the
moment of fracture, and not, as in ductile materials, with the work performed in extending a crack
across a section of the specimen. It has been
found that the mean impact resistance of a particular glass specimen will vary greatly, depending upon test conditions. This is shown in the
results of Figure 25 (Reference [29]) where the
test variables included plate thickness and
striker weights and velocities. The rapid increase in the impact energy of the 0.189-inch
plates at the lower velocities is of particular
interest; it was found to result from an increase
of damping effects in the structure at the lower
velocities. This demonstrates that damping may
have a pronounced influence on the impact resistance of glass, and of other materials.

MEASURING BREAKING STRESSES

Various methods of measurement may be used
to determine the magnitude of breaking stresses
in glass. None of these methods can be considered to be entirely accurate under all circumstances.

For simple types of tests stresses are usually
computed from the breaking load by means of an
appropriate stress formula. The elastic deflection can be utilized in a similar manner. Suitable
stress and strain formulas are found in many
textbooks, for instance, References [27] and
[28]. There are test conditions where these methods are not entirely satisfactory, so that other
measurements are used instead.

The simplest stress equation is that for tensile stress, which consists in dividing the load
P by the section area A, or

$$\sigma_T = P/A . \tag{13}$$

It has already been shown by Figure 21 that
bending moments may increase the maximum
stress across the section; in some instances,
they may double the maximum stress.

Another simple equation is for a bar or strip
in flexure,

$$\sigma_B = \frac{M y}{I} = \frac{M 6}{b h^2} \tag{14}$$

where M = the maximum moment,

y = the distance from the neutral axis,
and

b and h = width and thickness, respectively, of the section.

This equation is accurate only under certain
conditions. When the ratio of thickness to length
becomes relatively large, corrections should be
applied. When this ratio is small and deflections
become excessive, other corrections are applied.
Furthermore, friction between the specimen and
its supports will introduce components of membrane stresses. If the testing equipment is not
properly designed and adjusted the loads on the
two supports may not be equalized, nor the stress
distribution across the width of the strip. These
conditions can lead to local stresses which
differ materially from computed values.

Resistance types of strain gages are often
used to determine stress values. Limitations
are found where the fracture occurs in a region
of high stress gradient, or where the position of
the origin cannot be predicted. Polarized light

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and the polarimeter can be employed in a manner similar to that of the strain gage, but its use is still more restricted.

As will be discussed later, the breaking stress can be estimated from markings on the surfaces exposed by the fracture. This method has a wide application and has great utility if properly used.

It may be noted that stress values obtained from the applied load, from overall deflections, and from strain gages will register only the component of stress produced by the applied load. The polarimeter and the markings on the fracture surface register the combined stress, including any residual stress present in the glass. This distinction is important and should be made when the data are recorded.

FRACTURE ANALYSIS

Fracture analysis includes the examination of the fracture pattern, the fracture surfaces in general, and a more intensive study of the region in the vicinity of the origin. Taken as a whole, this type of analysis can furnish much information about the conditions involved (regardless of whether the fracture occurred during an observed test or in service where details regarding the event may be almost entirely lacking).

Some of the information obtainable from fracture analysis is listed briefly below. Other details may be found in References [6] and [30].

(1) The orientation of the tensile stress component responsible for fracture. This stress acts in a direction normal to the plane of the fracture surface.

(2) Lines usually visible on the fracture surfaces, such as are indicated in Figure 26, indicate the direction of crack propagation.

(3) Some of these markings and lines define crack velocity, and consequently the severity of the fracture process. The extent of fragmentation of the glass, particularly around the origin, also indicates fracture severity.

(4) The origin of the break is located within the fracture mirror (see Figure 7).

SMALL FORK OCCURRED HERE   MATTE SURFACE OR STIPPLED ROUGHNESS   END VIEW
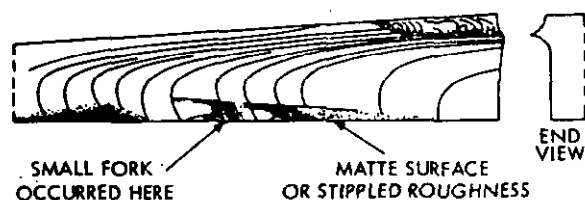
FIGURE 26. Fracture across a Section of Annealed Glass Resulting from Impact. Origin not included. From Shand, reference [6]

(5) The magnitude of the breaking stress may be estimated from the dimensions of either the fracture mirror or the fracture flaw.

Small undulations appear over the fracture surface, which, under suitable illumination, may be observed as lines and which indicate the direction in which the fracture moved. Figure 26 illustrates those lines on the surface of a glass fragment. They appear as waves surrounding the origin, so that in this case the origin was to the right of this fragment, on the bottom surface (that is, the fracture moved to the left). The inclination of these lines to the lower edge can be used to determine the velocity of the fracture along this edge. Several points where the matte surfaces begin show that the critical velocity was reached. The difference in inclination of the lines at the lower and upper surfaces show that a large bending component existed, with the lower edge of the glass in tension.

With larger fragments, the direction of propagation can be marked on each edge, so that when the fragments are reassembled the fracture can be traced back to where it started. With luck, even small fragments bearing the origin can be identified. The fracture mirror, a flat, smooth surface surrounding the originating flaw, is usually clearly recognizable. A small mirror with its fracture flaw is shown in Figure 7.

25. Breaking Stresses from Flaw Size (Reference [30]). The predominant weakening flaw in glass is a small crack which penetrates the surface. The planes of these cracks are more or less semielliptical in shape. The
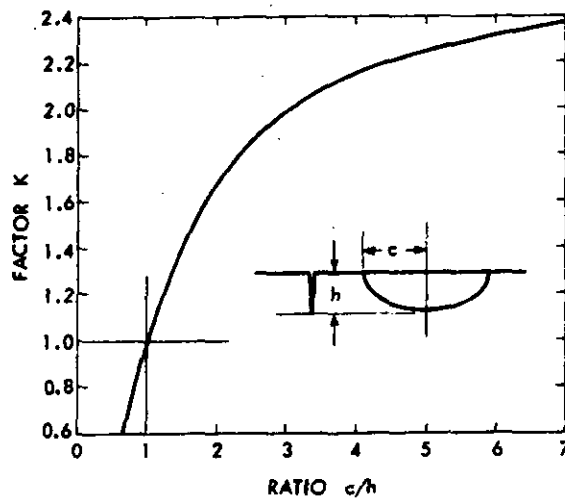
FIGURE 27. Stress-Raising Characteristics of Flat, Semielliptical Flaws Compared with Semicircular Flaws. Glass industry, reference [30]

original form of these cracks is usually distinguishable on the mirror after fracture, so that the dimensions of its axes can be measured with a microscope. The relative severity for any semielliptical flaw can be expressed in terms of
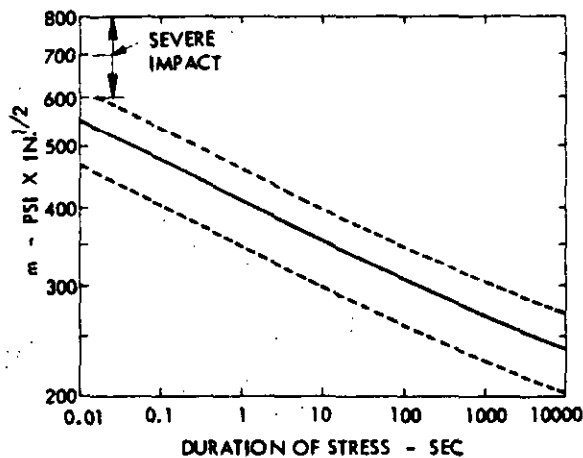

FIGURE 28. Relative Breaking Stress of Soda-Lime Glass as a Function of Stress Duration (Mean value and probable limits shown). Glass industry, reference [30]

an equivalent semicircular flaw, using Figure 27. The effective depth $h_e = Kh$.

The breaking stress resulting from any flaw is not constant, but depends on the extent of stress fatigue involved. The correlating factor, m, is shown as a function of stress duration in Figure 28, where

$$m = \sigma_a h_e^{1/2} \quad,$$

or

$$\sigma_a = \frac{m}{h_e^{1/2}} \cdot \qquad\qquad (15)$$

where

σ_a = nominal breaking stress (psi), and

h_e = effective flaw depth (inches).

In order to choose a suitable value of the factor m, some information on the time delay is essential. This can be determined either from direct knowledge of how the fracture occurred or from the general characteristics of the entire fracture surface.

This method gives the true breaking stress, including components of both the applied load and of residual stress. If the fracture is well defined, the estimated stress is usually accurate within 15 to 20 percent.

26. Breaking Stress from Mirror Size (Reference [30]). The mirror represents the expanded dimensions of the fracture crack at the moment when the critical velocity is reached, consequently the corresponding stress is independent of stress fatigue.

In the case of a mirror such as is shown in Figure 7, it is possible to correlate breaking stress with mirror depth, but many mirrors are of the form indicated in Figure 29, particularly when caused by bending stresses, so that the depth cannot be determined. Consequently, it is more convenient to correlate breaking stress with the mirror width, w. In large mirrors, this width is sometimes measured in a plane perhaps 0.004 inch from the original surface of the glass,

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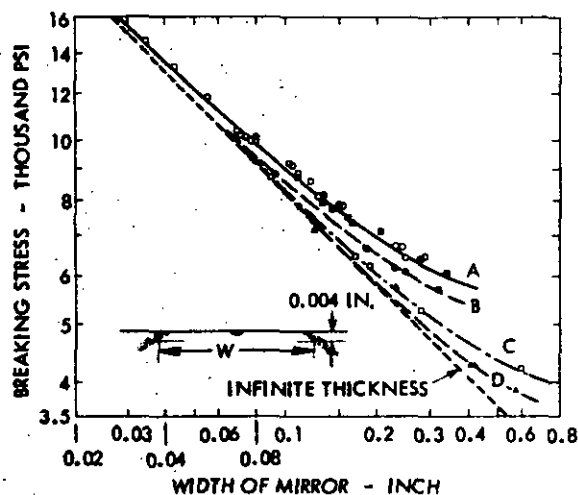
FIGURE 29. Breaking Stress versus Mirror
Width for Strips of Soda-Lime Glass
Broken in Flexure. Sections of
strips in inches: A, 0.09 x 0.75;
B, 0.09 x 1.25; C, 0.19 x 1.25;
D, 0.22 x 1.25. Glass industry,
reference [30]

in order to obtain greater uniformity. Figure 29 shows the relationship between breaking stresses and mirror width for soda-lime glass strips of different sections. It is apparent that this method is not applicable for lower breaking stresses, less than 5,000 to 8,000 psi. For these lower stresses the flaw method must be used.

The mirror method is both simple and effective. It gives the true breaking stress, including residual stresses, with an expected accuracy of 5 percent.

The values given in Figures 28 and 29 are representative of soda-lime glass. In some other compositions, such as lead-alkali glasses, the stresses will be somewhat lower, and for aluminosolicate glasses, somewhat higher.

The fracture surface illustrated in Figure 7 was produced by impact. The effective depth of the flaw b_e was found to be 0.00043 inch, so that the breaking stress was estimated to be 33,000 psi using the flaw method. The mirror width was 0.0052 inch, so that the breaking

stress was estimated to be 36,000 psi using the mirror method. From other data the time delay for fracture was determined roughly to be 0.001 second.

STRUCTURAL DESIGN OF GLASS

Structural design is based on the concept that there is some value of stress below which the material will not fail under the conditions imposed. The function of design is then to utilize the material in such a way that this stress will never be exceeded in service. Brittle materials do not behave under stress in the same manner as materials with some degree of ductility, so that approaches to matters of design will differ for the two types of materials.

27. Minimum Breaking Stress. Tabulated data are available for engineering materials which provide information on yield point, ultimate strength, elongation, reduction of area, and elastic properties, based on chemical composition and heat treatment. These data are often shown for various temperatures. With such formation, using established procedures, it is possible to design many types of structures to meet specified requirements. Corresponding data cannot be compiled for glasses; being brittle, there is no yield point, elongation, or reduction of area. Breaking stress is not an explicit function of composition but of workmanship, that is, the severity of flaw in the particular components under consideration. Any effect of heat treatment results mainly from the magnitude and distribution of the residual stresses set up. This leaves the elastic properties as the only data which may be listed.

Variances of strength are not only wide, but differ from one product to another. There is no fixed relationship between average and minimum values, so that the minimum breaking stress must be determined individually for each case considered. Tests such as those represented by Figure 9 can be used to show the distribution of breaking stresses for a population. In order to obtain a reasonable evaluation of the weaker members, it is desirable to use a sample of 50 specimens or more. This is because no reliable statistical method has been devised for extrapolating these curves to lower percentile

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values. Neither the gaussian distribution (expressed in terms of averages and standard deviations) nor the more flexible Weibull method is consistently reliable.* Hundreds of series of tests on glass products of various types have been used to check these methods. The difficulty lies in the fact that weaker members may follow a distribution function which is unrelated to that of the members in the median range. This results from a bimodal distribution [31]. It is essential to obtain data on the weaker members experimentally.

The probability of the occurrence of a severe flaw in a large surface area is greater than in a small area; consequently, the breaking stresses tend to be lower when larger areas are involved, as has been shown specifically in Figure 22. Statistical methods, such as that of Weibull, can be used to integrate the fracture probability as a function of area. However, discrimination must be used in the application of statistical procedures [31].

Stress fatigue must also be considered in determining the minimum breaking stress. Tests to obtain data on the distribution of strength, such as in Figure 9, are normally taken under short-time loading with constantly increasing stress. The effective duration of the breaking stress under these conditions may be taken roughly as the time interval required for the final ten percent increase load. Thus, if the total time from zero load to fracture is 40 seconds, the effective duration of the breaking stress is four seconds. From stress-time curves of the type of Figure 6 the corresponding fatigue limit can be evaluated. It is often about 35 or 45 percent of the short-time stress. If a more precise evaluation is required, special long-time tests may be performed. Such tests are normally continued for about three weeks in order to reach the fatigue limit.

Other means can be used to find the probable minimum breaking stress. If routine control tests have been made on the strength of similar products, the data, which may cover a considerable period of time and a number of manufacturing runs, may give a satisfactory answer. Another means is to make proof tests on the components after they are manufactured. In this way the weaker members can be eliminated from the completed product. The loads or stresses used in proof tests should be coordinated with the desired long-time minimum stress, and this stress should be maintained for a period of at least one minute. When shorter periods are used, the possibility of weakening the component without actually fracturing it is increased.

28. Structural Applications. When the probable minimum breaking stress has been established, design work can proceed. Working stresses will, of course, include a suitable factor of safety. Brittleness introduces several specific limitations into the design of structures.

a. Notch Sensitivity. Notches, fillets, and holes develop stress concentrations, the relative values of which, based on *elastic deformations*, have been computed for many geometrical forms. For metals with a considerable degree of ductility, the local yield in regions of high stress relaxes these concentrations, so that *their weakening effects are reduced* correspondingly. Under conditions of steady loading, the ratio of the theoretical stress to the relaxed stress is referred to as the "ductility ratio," or the "notch sensitivity index" (see Weiss, et al., p. 87, and Gerard, p. 111, Reference [16]). In metals these ratios may drop to a value of only a few percent, so that the presence of notches is not serious. Under cyclic loading the corresponding ratio, referred to as "notch sensitivity index in fatigue," becomes much greater, ranging from 0.40 or 0.60 for notches of small radius to

*The gaussian distribution, being symmetrical about the mean value, requires only two parameters. The Weibull distribution is not symmetrical. It employs one parameter which is related to a fracture probability, but not usually 50 percent, that is, not the median value. A second parameter is called a material constant and is related to variance or scatter of data. For convenience, a second stress value is sometimes used. It represents the minimum breaking stress for the population, the quantity of greatest interest to designers. A fourth parameter is the volume (or surface area) of the specimen.

values approaching unity for notches of larger radius [32]. For glasses and other brittle bodies the ductility ratio is unity for conditions of both steady and cyclic loading. There is no relaxation of the concentrated stresses from their theoretical values. Designs for brittle materials must be examined for all geometrical discontinuities which might result in stress concentrations (and provision must be made for these stresses). As far as practicable these discontinuities should be removed from regions of higher stresses.

Sometimes holes or grooves are formed by drilling or grinding. If the flaws resulting from these operations are not removed, weakening effects may be considerably greater than those indicated by the theoretical stress concentration factor.

While the procedures used in determining the ductility ratio will compare the degree of ductility of two ductile materials, or a brittle one, they fail to discriminate between the lack of ductility (brittleness) of two brittle bodies. Other procedures must be substituted for this purpose.

b. Local Yielding. It is well recognized that certain components of metal structures may be stressed locally beyond their yield points, either during fabrication or later in service, without appreciable weakening of the structure as a whole. A simple illustration of this is represented by the bolting of a plate over an opening. If the fit between the plate and its seat is imperfect, the plate may deflect permanently when bolted in place. This local yielding of the metal of the plate will seldom affect its performance in service. A glass plate subjected to this treatment will fracture unless special measures are taken to prevent failure. In one instance of this type, it was found impracticable to provide a flat seat for a glass window. Failures on assembly occurred frequently, until the thickness of the glass was increased sufficiently so that it could resist the bending moments caused by assembly as well as the pressure stresses.

When a structure consists of several components, these may be fitted and joined so that

the distribution of forces between components differs materially from that intended. If this condition becomes serious, the overstressed members when ductile may yield locally in order to compensate for the poor fitting, but for glass the result may be fracture. Thermal stresses can produce a similar situation.

29. Impact. When a structure is subjected to impact or shock a quantity of energy, depending upon the severity of the impact, will be transferred to the structure. This energy should be absorbed without failure. When deflections are held within the elastic limit of the material of the structure, the energy which is stored elastically may be one to ten times for metals what it is for glass. If permanent deformations occur in the metal, this ratio may be increased greatly because these deformations cannot occur in glass. By accepting limited damage, a metal structure can sustain impacts many times more severe than can glass. If some provision for damping can be introduced into the structure, the impact resistance of glass can sometimes be increased significantly.

30. Compressive Forces. It is well known that the strength of glass in compression is much greater than in tension, consequently, designs should be arranged so that glass will be used in compression as extensively as possible. Even when the forces are compressive, problems of strength remain. In pure compression, the breaking strength of glass may be considered to be almost unlimited; but at discontinuities, particularly at surfaces, stress concentrations occur which usually include a component of tension. Some of the results of these concentrations, which are difficult to reduce to small magnitudes, let alone eliminate, are discussed briefly under the subject of Strength (Chapter 3, paragraph 17, g, Glass under Compressive Loads).

One instance of the weakening of glass by compressive forces occurs in glass pressure windows. When the glass is subjected to excessive bolting pressures, its ability to withstand fluid pressures may be decreased seriously. In some cases this decrease has been in excess of 70 percent.

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If the contact pressure between a hard object and a glass surface is excessive, the glass may be damaged seriously. Cushioning material is sometimes used in order to distribute the compressive force over a larger effective area.

The impacts of small objects may injure glass surfaces. Sometimes the glass is crushed over a small area and perhaps scratched. Abrasion by hard objects will produce similar effects. As a consequence, glass structures may be weak-

ened by service conditions, and protective measures must be taken in certain cases to reduce such weakening effects.

On the other hand, glass is seldom affected by chemical attack, which may weaken metal structures when exposed to corrosive conditions.

When prestressed glass is used, the weakening effects of surface damage are greatly reduced.

Chapter 5
Applications

GENERAL

The applications for which any material is suitable are determined by its properties, and by manufacturing difficulties and costs. The properties of glass have been reviewed in Chapter 3. It was shown that glass is unusual because it combines transparency with rigidity and hardness, plus an ability to withstand relatively high temperatures and the action of chemicals. Furthermore, glass can be fabricated readily into many commercial products. Glass has its widest use in the preparation, transportation, and storage of foods, beverages, drugs, and chemicals. A second basic use is that of glazing for many purposes. It is the most widely used of all optical materials and has many applications in this field. Glass has limitations for structural purposes because of its brittle characteristics.

In the military field the applications of glass are basically similar to corresponding civilian uses. Specific requirements must sometimes be modified to meet military needs. The applications considered here cover only a few representative uses. In the following discussion of Windows, an attempt is made to show how a simple glazing unit can be modified and developed to meet special and more exacting requirements.

WINDOWS

Windows are here considered from the broad standpoint of any transparent part of a wall or enclosure. The basic application is the use of glass for windows of buildings. Developments include the ability to withstand pressure, high temperature, severe shocks, and even the impact of bullets.

a. Building Glazing. Various types of flat glass are used for the common glazing of buildings. Information on sheet glass, plate glass, figured glass, and wired glass is found in Federal Specification DD-G-451. Details regarding the application of glass for this purpose are in the BOCA* Basic Building Code [33]. Window sheet is ordinarily used for small panes, and plate glass or float glass for large panes.

The mechanical forces which must be supported by these panes include those resulting from wind pressures, differences of static pressure caused by the operation of ventilating equipment, and also relatively mild pressure shocks resulting from various causes. The dynamic pressure produced by a wind of 100 mph velocity is roughly 25 lb per ft^2. This pressure may act either inward or outward on the building wall. If the ventilating equipment produces a positive pressure within the building, the total outward pressure may exceed the inward pressure,

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* Building Officials Conference of America.

consequently the outer holding devices for the glass are of particular importance, since the total force acting on a large pane may amount to several tons. The resultant stresses in the glass are not readily determined.* Experimental work has been carried out to determine the static pressures required to fracture rectangular glass panes of various sizes and thicknesses [7] and [33]. The resultant data are used in selecting glass for windows. In addition, the framing structures for larger panes should have their deflections kept within low limits.

Heat transfer problems have resulted from the use of large glazed areas in buildings. Heat loss through windows in winter represents not only additional heating requirements, but also means discomfort for persons stationed near them. The use of double glazing can reduce this problem, but will not eliminate it. Heat gain from the sun's radiations also presents a problem. This gain may reach values of the order of 250 Btu per hr per ft^2, and additional heat may be transferred by conduction-convection effects. Peak requirements for the cooling of buildings may be increased greatly because of these heat gains. The most effective means for reducing these effects is probably the complete shadowing of the glazed areas, but this is often not practicable. Other means include employing heat-absorbing glass and the use of heat-reflecting coatings on the glass.

The heating of the glass by the sun will develop thermal stresses. Under most conditions these stresses are not critical in value, but may require consideration in the case of heat-resisting glass and curved panes.

For most buildings used for military purposes, the glazing requirements will not differ materially from those of buildings for other purposes.

b. Safety Glazing. This type of glazing is used in buildings under certain conditions, and in land vehicles, marine craft, and aircraft. It includes laminated, tempered, and wired glass, and also some types of sheet plastic. Safety glazing is used in building areas within the reach of active children, for doors with large areas of glass, and for windows which may be exposed to unusual conditions of shock. USA Standard Z97.1 includes requirements and acceptance tests for safety glazing to be used in buildings. The impact test designated consists in striking the pane with a 100-lb shot bag, moving at a velocity of 16 ft per sec (energy of 400 ft/lb). The glazing material is considered to be satisfactory if it remains intact to the extent that no opening exceeds a certain specified size, or, if the glass disintegrates (as in the case of tempered glass), no fragment exceeds an indicated dimension. Tempered doors in buildings should comply with these or similar requirements.

In some military buildings the glazing has been required to withstand neighboring explosions resulting from enemy action, and in other instances explosions in test areas. For these conditions, the requirements may be more exacting than those given in USAS Z97.1.

In the case of land vehicles, the glazing specifications will depend somewhat on the position of the glazing with respect to the vehicle. In general, the requirements are most severe for the windshield, because it is probable

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* Most stress formulas for rectangular plates with large deflections are based on hinged edge support rather than simple edge support, as found in most windows. Test results show that the stresses for these two conditions are quite different.

that the heads of occupants may be thrown against this glazing in case of an accident. If the windshield is too rigid, a skull fracture may result; but if it fails under impacts which are too low, heads may penetrate the glass, so that serious or perhaps fatal lacerations may be inflicted on the head and neck. USA Standard Z26.1, for vehicle glazing, specifies laminated safety glass for windshields.

In 1966 this standard was revised in accordance with improvements made in laminated glazing. The plastic interlayer between two layers of 1/8-inch glass was increased from 0.015 to 0.030 inch, and the bond between interlayer and glass was modified to permit greater elongation of the former. The effect of these changes has permitted the windshield to deflect more, and thus absorb more energy, as is indicated in Figure 30. The modified construction has raised the impact velocity for failure from 8 to 10 mph to 30 mph. An analysis of casualty statistics for automotive accidents indicates that this new product has materially reduced the severity of head injuries.

In a more recent development, windshields have been assembled with an outer layer of plate glass 0.105-inch thick; an inner layer of chemically prestressed glass 0.070-inch thick; and a
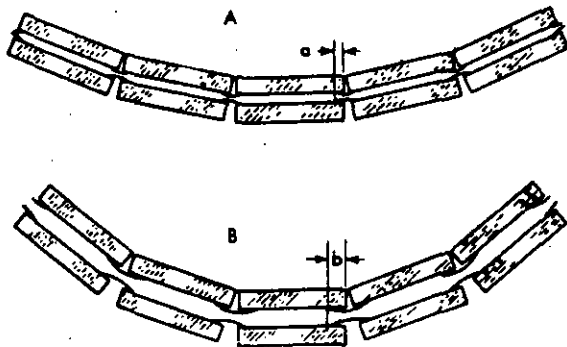
plastic interlayer 0.030-inch thick, as mentioned above [34]. This laminate will not only permit a still greater deflection of the windshield, but also, the inner layer on fracturing will disintegrate into such fine particles that the severity of head lacerations is reduced still more.

Military specification MIL-G-3787 corresponds with USAS Z26.1 in a number of respects.

Bullet-resisting glazing is sometimes considered as one type of safety glazing. It consists of alternate layers of glass and plastic. The impact of a bullet may represent several thousand foot-pounds of energy, the major portion of which must be absorbed by the plastic interlayers rather than the glass.

USA Standard Z26.1 lists four classes of bullet-resisting glazing for vehicles, ranging in thickness from 1-3/16 to 2 inches. The two exposed surfaces are specified to be glass. Details of procedures for the ballistic tests are not included, but must be obtained from other sources. Military specification MIL-G-5485 refers to bullet-resisting windshields for airplanes. Nominal thicknesses range from 1/2 to 3 inches. The procedures for the ballistic tests are given in detail. The obliquity of the path of the bullet with respect to the glazing is specified as a function of the weight of the bullet and the weight of the glass components of the window per square foot. The glazing is considered to have failed when:

(1) The bullet core or core fragments penetrate the unit completely.

(2) When through-openings are made by either bullet or glass fragments in a plastic sheet mounted six inches behind the window assembly.

Military specification MIL-A-46108 (MR) refers to transparent composite armor for aircraft, marine, and automotive applications. It differs from the other specifications, because the rear ply is a sheet of nonspalling plastic rather than glass. Another specification is

FIGURE 30. Constructions of Former (A), and Present (B), Laminated Glass for Automotive Windshields, Showing Increased Ability of B to Deflect

referred to for detailed information on the ballistic tests. The definition of bullet penetration is generally similar to that of MIL-G-5485. The light transmittance of the unit is required to be 80 percent over the entire visible spectrum. In order to meet this requirement, not only must the light absorption coefficients of the glass be low, but the light loss at the various interfaces between glass and plastic must also be low.

c. Airplane Windshields. The development of airplane windshields has followed the demands of ever-increasing operating speeds. Early modifications included increased thicknesses of the plate glass used in the laminate, and later, tempering the glass for greater strength. The plastic interlayer was then extended beyond the glass, so that it could be attached directly to the airframe. In order to provide greater strength, the extension was reinforced with sheet metal [35]. The fastening of the interlayer to the airframe provides protection against decompression of the cockpit in the case of a glass failure.

Systems were also devised for deicing and defrosting the windshield in response to certain flying conditions. In one method, an electrically conducting coating is applied to the glass surface so that it can be heated with electric currents. This coating is commonly applied to the inner surface of the outer layer of the laminate.

Further increases in speed raised the windshield temperature to a point where the residual tempering stresses in the soda-lime glass relaxed with time, and where the flow of the plastic interlayer became excessive. The soda-lime glass was replaced with a tempered aluminosilicate glass, which permitted an increase in operating temperature of 130 °C or more; also, plastic interlayer materials were developed which would withstand much higher temperatures than the polyvinyl butyral plastic then in use.

d. Space Craft. Temperatures reached by the surfaces of space craft during reentry into the earth's atmosphere are very much higher than those attained on aircraft windshields, so that

difficult problems had to be solved before satisfactory windows could be provided for these craft [36]. The windows actually used in the Apollo spacecraft for moon journeys consisted of assemblies with several panes of glass. The protective outer shield, which is subjected to the highest temperatures, was of silica glass. The two inner panes, subjected to lower temperatures and lower thermal stresses, were of tempered aluminosilicate glass. These inner panes must also support the differential pressure between the inside of the craft and outer space. The entire window assembly was designed to reduce the transfer of heat by conduction and convection to a minimum. Furthermore, the glass surfaces themselves were coated with thin films which permitted the transmission of most of the light, but reduced the transfer of heat by radiation. These windows have met the exacting requirements of this service.

e. Pressure-Resisting Windows. Glass windows of many types and for many purposes are required to withstand pressure differences. Some of these windows are flat plates, which are clamped against gasketed seats by means of bolted metal flanges. This general type of window is used for sight windows of tanks and vessels under pressure and for liquid level gages in steam boilers. Many pressure tests have been made on this type of window; the results have shown that bursting pressures are influenced greatly by the design of the mounting structure and by details of assembly procedure. As a consequence, it is impracticable to assign any pressure rating to the glass (considered alone), but only to the composite structure, consisting of the glass and its mounting assembled under prescribed conditions. Test data [6] show specifically that when the mounting structure lacks rigidity, when the fit between glass and its seating is not satisfactory, when the gaskets are not suitable, and when the forces used in bolting the holding flanges are excessive, the bursting pressure of the glass may suffer severely. In some cases the reduction of bursting pressure has been as much as 90 percent. When used for high pressures, this

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type of mounting loses much of its effectiveness. Some tests [6] indicate that when the ratio of thickness to diameter is increased for higher pressures the allowable bending stress computed by the simple plate equation decreases. For example, with a ratio of thickness to diameter equal to 1.0, this computed stress drops to approximately 25% of its value when this ratio equals 1/10. The application of tempered glass for higher pressures can help this condition materially.

If the inner surface of the window is exposed to elevated temperatures, as in the case of liquid level gages on steam boilers, thermal stress components are added to those of pressure.

Suitable pressure ratings for pressure windows must take all factors into consideration, so that they are based on tests and also on experience. They should not be assigned to any glass component considered separately from its mounting structure.

Glass components of evacuated devices function as pressure windows. The viewing panel of a cathode ray (television) tube is an example of this. The load on a large panel of this type may amount to several tons, so that in order to develop reliable tubes for this purpose extensive efforts were necessary, both experimental testing and analysis. In some designs, the glass panel is fusion-sealed to a metal ring, which adds another phase to the problem.

Glass industrial piping, while not serving primarily as a window, is subjected to pressure, and must comply with specified test conditions (ASTM Desig. C 601). The spillage of certain fluid contents in the event of a pipe failure could constitute a serious hazard, so that a special structure (similar in some respects to laminated safety glazing), has been developed to prevent such occurrences. The glass pipe and fittings are wound with layers of glass fibers, and these layers are impregnated with a plastic material, which may be transparent when visibility is desired. With this reinforcement, even if the pipe were to break, spillage would be prevented so that suitable corrective measures could be taken.

Portlights for marine application must withstand the impacts of heavy seas. Military specification MIL-G-2697 states the requirements of tempered portlights of circular shape in various sizes. Acceptable strength is based on tests in which bending moments are applied around the rim of the glass (as noted in Chapter 4, Plate Flexure Tests, paragraph c, under Strength Testing and Measurement). This unusual test procedure may have been chosen to produce the effect of imperfect fits between the glass and the seating surface. Actual stress values in the glass are not indicated in the specification.

Explosion hazards exist in some military buildings, which necessitates precautions against the occurrence of sparks or flame. Explosion-resisting lighting globes reduce hazards from lighting installations. Explosive gases may penetrate into a lighting globe, where they can be ignited by a lamp failure or some other malfunction. Protective globes are required to withstand the pressures developed by such an ignition, and the surfaces across the joint must provide for the cooling of any gases which might escape, so that gases outside the globe will not be ignited. Tempered glass domes with heavy walls are used for incandescent lamps, and sections of industrial glass piping for fluorescent lamps. Requirements and tests which apply to these globes are included in the National Electrical Code [37].

f. Submersible Vessels and Craft. The exploration and study of ocean depths is important for both general and military purposes. Equipment intended for these studies has already been used for the location and identification of the remains of lost naval submarine craft, and for the recovery of military materiel from the ocean bed.

Because of its high strength during compression, glass has interesting possibilities in this field. In the case of simple shapes, such as spheres and cylinders, elementary analysis indicates that the wall stresses under conditions of external hydrostatic pressure should be entirely compressive. If this theoretical condition could be attained, these vessels would resist

failure at pressures up to the critical pressure for elastic instability. These pressures may be defined as follows:

$$\text{Cylinder}[38], \quad P_{cr} = \frac{0.25\ E\ (h/R)^3}{(1-\nu^2)}, \quad (16)$$

$$\text{Sphere}[39], \quad P_{cr} = \frac{0.80\ E\ (h/R)^2}{(1-\nu^2)}. \quad (17)$$

Where

P_{cr} = hydrostatic buckling pressure,

E = modulus of elasticity,

h = wall thickness of shell,

R = radius of shell at midpoint of wall, and

ν = Poisson's ratio.

Equation (10) is not applicable to most cylindrical hull structures because it applies only to cylinders of indefinite length. For shorter cylinders, the critical pressures are increased by end support. Experiments have shown that when the length is at least six times the diameter, breaking pressures of glass tubing will not materially exceed the computed critical pressure. For a glass-ceramic cylinder with an effective length of only 80 percent of its diameter, pressures reached six times the critical value without failure [40].

When a sphere is compared with a cylinder, its effective length is very short with respect to its diameter. With wall-thickness ratios of practical designs, the critical pressure of a sphere may be 15 to 30 times that of a long cylinder.

When a sphere is composed of two hemispheres connected at a joint, or a single hemisphere attached to a metal ring at a joint, the conditions found in the unjointed hemisphere no longer exist. The discontinuity represented by

the joint introduces additional stress components at the interface region. Some of these components will be tensile, as noted in Chapter 3, with the effects on failure as shown in Figure 12. Considerable development work has been carried out on the detailed design of joints to reduce these undesirable stress components, but the basic problems introduced by the discontinuities of the joint have not yet been completely solved.

Small glass spheres containing instruments have been tested under hydrostatic pressures up to 10,000 psi, and have been used for making measurements at depths of 6,000 feet or more. Hydrostatic pressure tests have also been made on large hemispheres, with diameters up to four to five feet. The results of such tests have not been entirely conclusive, although there are indications that some of the problems can be solved.

g. *Windows for Selective Transmission.* Some window applications are based on the ability of glasses to transmit certain bands of the electromagnetic spectrum and to absorb others. Differences in absorption over the visible range are responsible for the effects of color in lighting. Colored lenses for lamps have many applications for the control of traffic on railways, highways, airways, and on the seas and waterways. They are also used for other forms of signaling. In certain types of military signaling secrecy is maintained by utilizing parts of the spectrum beyond the visible range (the ultraviolet or the infrared). Receiving equipment must, of course, be responsive to radiations of the wavelength used. Figure 13, curves H and K, shows some characteristics of glasses which absorb completely within the visible range, but transmit in the infrared or ultraviolet.

Some types of military rockets are directed towards target airplanes by equipment which is responsive to the heat of the exhaust. This equipment is housed in a dome of glass which will transmit radiations of at least 5.5 microns wavelength. Calcium aluminate and other glasses [2] may serve this purpose. Other types of missiles make use of radar for guidance purposes. The radar antenna is mounted in the

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nose of the missile and the radiations are transmitted through an ogival cone or radome. The reflected wave is also transmitted by this radome to the receiving equipment. The material of the radome must be such that it can withstand high temperatures, and retain low dissipation and loss factors under these conditions. Distortions caused by the refraction of the radar waves in passing through the material must be small. The material must be of relatively high strength, and it must be possible to form the radome accurately to shape. Certain glass-ceramic bodies fulfill these requirements more satisfactorily than glasses, so that they have been used for this purpose.

Radiation protection windows are used for observation in enclosures containing sources of high-energy radiations. Vision must be sufficiently satisfactory for the operation of manipulators within the enclosure. The radiations are usually X- or gamma rays, which are absorbed most efficiently by the lead in the window. Glasses for the absorption of these radiations may contain up to 76 percent lead atoms, as noted in paragraph 23 of Chapter 3. Military specification MIL-G-43349 covers such glasses. Further information on radiation absorption and "lead equivalents" will be found in Reference [6].

FIBER OPTICS

Fiber optics defines a system of light transmission along transparent fibers. When many fibers are arranged suitably in bundles, images can be projected from one end of the bundle to the other. A condition of total internal reflection from the circumference of the fiber is essential to the functioning of this system. Consequently, when fibers are combined in a bundle the core of each fiber must be surrounded with a glass of lower refractive index. For some purposes the resolution of the fibers in these bundles is roughly 0.001 inch, but for special purposes this may be reduced to 0.0002 inch.

Although fiber optics have many uses, one of particular military importance is that of night observation of objects in very dim light. It has

been noted by Kapany [41] that the "combination of a high-quality lens system and a conical fiber bundle can function as a high-speed lens so that photographs can be taken by moonlight." This principle has been extended greatly so that enemy movement can be observed by the dim light of the stars [42]. The image intensifier includes a lens and a bundle of optical fibers to conduct the light to a "photocathode of a light-sensitive film. Electrons emitted by the film are accelerated by an electric field and hit a phosphor screen, which gives off light." [42]. It has been reported that the light is intensified 40,000 times.

FIBROUS GLASS

When glass is drawn into fibers it does not change its physical properties, except for changes of a minor nature caused by extremely high rates of cooling. The characteristics of fibrous glass products, however, are more like those of organic fibers than those of massive glass. Fibrous glass products include forms of wool, textile materials, and composite materials in which fibrous glass is used as a reinforcement of a plastic. (For general information on fibrous glass see Reference [6].

31. Wool Applications. In the form of wool the glass fibers may constitute as little as one percent of the volume, the remainder being air. The wools have no structural properties and can be compressed into much smaller dimensions with the use of little force. The entrapped air, which is prevented from circulating freely, gives the wool excellent properties of thermal insulation. When used for insulation at higher temperatures, a greater density of fibers is found to be more effective. For some purposes mineral fillers may be added to the wool. If the wool is compressed and the fibers then bonded together with small amounts of adhesive, it becomes an insulating board with a limited degree of rigidity. These products are used for insulating panels, for roofing material, and in some instances for sound insulation of light weight. With added filler, various products are suitable for sound absorption.

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Wool products are used for the thermal insulation of buildings, airplanes and ships, home appliances (refrigerators, ranges), and refrigerating compartments. If moisture permeates this insulation and freezes, the insulating properties of the material will be seriously impaired. For some applications the wool will be enclosed and sealed so that this condition will not occur. This precaution is particularly important in the case of refrigerated compartments [6].

The compressed wool products, with or without fillers, are used for industrial insulation at the higher temperatures, and on pipes, tanks, and other heated parts. When the temperature reaches 1,000°F (535°C) fibers of one of the silica glasses should be used. Oils used for fiber lubrication and adhesives which can ignite are eliminated in high-temperature insulation.

For applications in airplanes and ships and on various types of military equipment, the properties of nonflammability and of lightweight are important.

32. Textile Fibers and Filaments. In addition to the properties found in glass wool fibers, the textile fibers have high mechanical strength, a property which is an important factor in many applications. The modulus of elasticity of the glass fibers is also much higher than that of organic fibers, so that in order to obtain the same flexibility and smoothness in textiles the individual fibers must be much finer. A special textile fiber has been developed with a diameter of only 3.8 microns (0.00015 inch), which is much finer than the natural and artificial fibers of conventional textiles. Glass fibers of considerably coarser size are entirely suitable for industrial and other purposes.

The tensile strength of glass textile filaments is frequently stated to be 500,000 psi, or even more. Such strengths will be reduced by damage received in handling, in various textile operations such as spinning, weaving, and braiding, and in the application or removal of textile sizes [43]. Reported values of strength range upward from somewhat more than 100,000 psi to 650,000 psi, depending upon the particular operations performed and the care used in handling the fibers.

While this order of strength is much greater than that measured for massive glass, the increase represents only a part of the advantage of the textile fiber over massive glass. In massive glass it is expected that the elongation under conditions of fracture will amount to 0.1 − 0.4 percent, which is insufficient to permit equalization of the stress across the section of the glass. With glass fibers the corresponding elongation will be nearly 10 times these values, so that the stress equalization will be relatively much greater. Furthermore, the individual fiber in a yarn or cloth will not be straight, but somewhat wavy. Under stress it will tend to straighten, so that this ability to stretch permits further elongation and stress equalization under load. These characteristics correspond in some degree to ductility or plastic flow in metals.

When at some point of weakness on the surface of massive glass an overstress produces a crack, this crack will propagate into the section, carrying with it (in ever increasing degree), its weakening effects. In this manner failure becomes complete. When a single fiber in a textile construction breaks, either from weakness or from overstress, the fracture crack cannot propagate into the neighboring fibers so that the fracture is confined to the particular fiber involved. The small portion of the load which had been carried by the broken fiber will then be distributed among the other fibers, with little resultant decrease of strength.

While the preceding analysis is oversimplified, these two characteristics have a pronounced effect on the structural capabilities of fibers as compared with massive glass. However, the structural applications of glass textiles are confined to those involving tensile stresses only.

Representative applications of glass textiles include drapes, wall coverings, and protective coverings where the nonflammable and decay-resisting characteristics of the glass are important (e.g., on aircraft and on shipboard). Textiles are made into protective outer clothing for workers engaged in extinguishing intense fires. Similar clothing, but of a very sophisticated nature, has been designed for and worn by

astronauts in spacecraft. While this use is limited, it is of outstanding importance in military development. Fibrous glass textiles are used for filtering, particularly for dry dusts at high temperature.

The noncorrodible properties of glass textiles are utilized in the protection of tanks and underground pipelines. The textile covering is impregnated with mastic to prevent the penetration of moisture. Roving and woven tape are used for insulating conductors of electrical equipment so that operating temperatures can be raised above those established for organic materials. Varnishes with which these coverings are impregnated must also be able to withstand these higher temperatures. Such insulation is essential for electric motors and other apparatus installed on many types of military equipment.

33. Fibrous-Glass Reinforced Plastics. While fibrous glass textiles have exceptionally high strength, they lack the rigidity which is essential to the vast majority of structural applications. This deficiency can be overcome to a very considerable extent by combining the fibers or textiles with plastics or resins to form composite bodies. The fibrous glass imparts tensile properties to these bodies, while the plastic matrix resists shear forces between fibers and thus promotes rigidity.

The mechanical properties of these composite materials are dependent on a number of factors [6], [44], and [45]. Basically they are a function of the properties of the fibers, the properties of the plastic matrix, and the interaction at the glass-plastic interface, which in turn is a function of the characteristics of the bond. Fibers may be in the form of continuous bundles or rovings, woven textiles, mats, or chopped fibers in short lengths. Rovings, textiles, and mats may be laid up to form laminates. The orientation of short fibers is much more likely to be random. The plastic material used for the matrix may be thermosetting (polyester, phenolic, or epoxy), or thermoplastic (polyethylene, polystyrene). Such plastics vary in their properties. Other variations result from the treatment and method of fabrication used. Strength and rigidity of the material increase, in

general, with an increase in the proportion of glass used in the composite. The properties of the bond between glass and plastic depend not only on the treatment of the glass surfaces, but also with the environmental conditions, particularly the presence of water.

Two problems are encountered when attempts are made to carry out accurate stress analyses for fibrous-glass reinforced plastics when subjected to loads [46] and [47]. The first concerns the interaction between glass and plastic at the interface. There are still the unanswered questions of just how the forces are transferred across the interface and distributed in the surrounding matrix, and how the conditions are affected by environment. The second problem is related to the distribution of forces over the various parts of the reinforcement. The arrangements of fibers under practical conditions may become very complex, with a degree of anisotropy which cannot well be represented by workable mathematical expressions. In many of the more complex designs, the work of the stress analyst cannot be accepted without experimental confirmation.

Reported data indicate that the dry flexural strength of fibrous-glass reinforced plastics commonly ranges between 20,000 and 75,000 psi. Corresponding values of elastic moduli in flexure may range between 1.5×10^6 and 5.5×10^6 psi. In addition to the effects of the environment, the strength of the material is influenced by both static and cyclic stress fatigue. Some data indicate that steady loads, long-continued, may decrease the breaking stress by amounts of the order of 40 percent, and that the addition of cyclically applied stresses may decrease the breaking stress by values of the order of 75 to 80 percent. In carrying out structural designs with these materials the possible results of environment, long-continued loads, and cyclic stresses require careful consideration.

Because of their desirable mechanical characteristics these composite materials have many applications of military interest. Many of these applications represent substitutions for wood or metal, particularly where savings of weight are desired. They are used for component parts of automotive bodies, parts of airplanes,

and hulls of boats (specifically, river patrol boats). They have been used to reinforce the tubes of small rocket launchers, the reinforcement of plastic pipe, and for light-weight armor.

a. Airplane Components. The design of airplane frames and components has become highly sophisticated because, in order to save weight, not only has the shape of the part become complex, but the properties of the material itself have been tailored to meet the structural requirements. As previously mentioned, the resulting properties may be highly anisotropic so that precise mathematical analysis may be beyond our present capabilities (Rogers [46].)

One limitation found in fibrous-glass reinforced plastics for stress-bearing members of airplanes results from low values of the elastic modulus. In general, this modulus cannot readily exceed one-half the value of the glass. For glass compositions ordinarily used, the modulus will seldom exceed 5×10^6 psi. Special glasses with higher elastic moduli have been developed for these fibers, but the modulus attainable in the composite is still much lower than those obtainable from other high-strength fibers. In the application discussed by Rogers [46], boron fibers with an elastic modulus of 50×10^6 were substituted for glass in parts of the component in order to increase rigidity.

b. Reinforced Plastic Pipe. Plastic pipe has definite advantages for military uses. It is light in weight so that it can be readily transported. It is noncorrodible and is an electrical insulator. Such pipe is available in pressure ratings adequate for many purposes.

Resins used for such pipe are normally thermosetting and tend to be somewhat brittle and weak [48]. The pipe consists of an inner plastic lining, the fibrous glass reinforcement (which may constitute 60 to 80 percent of the material), and a plastic matrix. The fibers are laid over the lining in two courses; in the first, the fibers are wound helically in order to resist the bursting pressure. The second course is laid parallel with the pipe axis, to resist the axial forces produced by the internal pressure.

Tests have indicated that the short-time bursting pressure of a two-inch pipe may be of the order of 8,000 psi, and that if this pressure is maintained for a matter of 5 to 10 years the bursting pressure may drop to nearly 10 percent of its short-time value. Temperature and environment will influence failure, so that suitable ratings will be determined on the basis of a number of factors.

c. Light-Weight Armor. During World War II there was a need for the protection of military personnel from fragments of grenades and mortar shells. A type of light-weight armor, known as "doron", was developed to meet this need [49]. The armor was a laminate consisting of about 16 layers of fibrous glass cloth of satin weave, with a matrix of 23 to 25 percent of a thermosetting resin. The thickness of the laminate was 1/8- to 3/16-inch with a weight of 1.3 lb/ft^2.

An interesting feature of this laminate was the use of textile sizing on the glass, which prevented a strong bond from forming between the glass and the matrix. This permitted the composite material to delaminate over a considerable area under the impact of a fragment. This motion of the fibers and matrix over an extended area distributed the impact and allowed a greater amount of energy to be absorbed. This same general principle has been mentioned in connection with automotive windshields and it is illustrated by Figure 30.

When formed, the laminate was cut into small panels which could be inserted in pockets in jackets to be worn by personnel. While tests indicated that this armor would furnish the desired protection from fragments, and would stop a pistol bullet, it did not receive full battle tests before the war ended.

Conditions encountered in the fighting in Vietnam differ materially from those of previous wars. A large proportion of casualties result from bullet wounds. The "doron" armor is not capable of providing such protection, so that a new development was undertaken [50]. The general principle paralleled that used in steel

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armor, where an intensely hardened surface breaks up the projectile and reduces its velocity, while a ductile backing absorbs the energy of the projectile. The armor developed consisted of, first, a spall shield of polyurethane rubber or ballistic nylon fabric, then a ceramic layer, slightly more than 1/2-inch thick, and composed of a hard ceramic body of alumina, boron carbide [51], or silicon carbide. This ceramic is intended to break up the bullet and to deflect it from its armor-piercing trajectory. Behind the ceramic layer is a plastic laminate similar to the "doron" armor and roughly 1/4-inch thick. These elements are all cemented securely together to form a single unit. A chestplate for body armor uses a ceramic part formed to a shape which will conform to the body of the wearer.

The direct impact of a .30 caliber bullet fired at close range and at a velocity of 2,700 ft/sec may spall and remove completely the ceramic layer over an area perhaps one inch in diameter, but the glass-plastic laminate will absorb the energy of the bullet and prevent its penetration of the armor.

This armor has already demonstrated its protective capabilities. It is used for personnel body protection, for aircraft pilot seats and panels for walls and floor, for shields of vulnerable aircraft components, and for deckhouse armor and gun shields. For purposes other than armor to be worn by personnel, thicknesses have been increased to provide protection against a .50 caliber armor-piercing bullet.

Chapter 6
Quality Assurance

GENERAL

High standards of quality and performance are achieved through the proper use of specifications. These specifications are intended to represent an agreement between user and supplier regarding the requirements to be met by the materials or products under consideration. Not only should these requirements be clearly defined, but also the procedures to be followed in determining compliance with these requirements. When test procedures and methods for evaluating results of such tests are not included, serious misunderstandings can occur.

A group of selected standardization documents relating to glass products is included in Table XI. This list includes Military Specifications and Standards, Federal Specifications and Standards, U.S.A. Standards Institute specifications, and American Society for Testing and Materials Test Methods and Standards. Many other specifications have been issued on special glass products which have not been included in this list. Federal Specification DD-G-451, which covers a wide variety of flat glass products, is sometimes applied in other specifications to glass which is to undergo further fabrication. Sections of USASI Z26.1, approved for civilian vehicles, are to be found in corresponding military specifications, such as MIL-G-3787. Specifications of the ASTM have been grouped with reference to their classification. Some of these specifications include details for sampling for acceptance tests. If not, MIL-STD-105 may be used for this purpose.

The complete designation of a standard specification will include a suffix indicating the date of its formal approval or its last revision. These suffixes may change from time to time so that they are not included in Table IX, except for two ASTM units which have a second and tentative form.

REQUIREMENTS

The functions which a glass component is to perform can usually be stated fairly definitely, but the requirements essential for these functions which can be written in a specification and then verified by some procedure may have to be expressed imperfectly in entirely different terms. Sometimes this requirement can be expressed in terms of a physical property. In other cases, performance may depend more on design and workmanship. Correlation between specified requirements and operating performance can be established by means of special tests, or for established products, based on experience.

The basis which may be employed for defining requirements may include the following:

(1) Glass properties. These may be stated explicitly or indirectly.

(2) Workmanship. This term is used here to cover all types of efects and imperfections which may be found in glass products.

(3) Functional Tests. These are intended to verify or confirm the operational performance of the entire component.

GLASS PROPERTIES

For some materials, particularly metals, various physical properties have been correlated with standard grades identified by chemical composition, often including specific processes or treatments used in manufacturing. These grades are covered with specifications. No such method of grading has been adopted for glasses. The chemical composition of some glasses is shown in Table I; these are only general types, however. Although some specifications imply a type of glass as described in Table I, exact compositions are seldom referred to. For example, in MIL-G-43349 for X-ray protective glass, the minimum content of Pb 0 is given as 61 percent.

Physical properties are specified more frequently. For optical components, for example, optical properties are of course important. The index of refraction and its variation with wavelength (called dispersion and sometimes defined by nu-value or Abbe constant) are requirements of this type. Optical glasses are commonly identified by type numbers, which represent both refractive index and nu-value. Thus, the type number 517–645 represents a glass with a refractive index of 1.517 and a nu-value of 64.5. In some cases, this type number is closely correlated with glass composition. Light absorption is also important, and it may be expressed as an absorption coefficient or as the luminous transmittance for a section of a specific thickness.

Although certain electrical requirements must be met by various electrical components, the influence of structure and design on results is such that actual measurements are ordinarily made on the complete component.

Thermal expansion coefficients may represent the requirements of products subjected to thermal stresses. Standard tests for measuring thermal expansion have already been mentioned in Chapter 3. The capability of successful operation at some elevated temperature is sometimes indicated as a requirement, but procedures for determining compliance are seldom given explicitly.

Strength is a characteristic which cannot be expressed as a property of the glass, because it will be influenced greatly by fabricating conditions. Strength is commonly determined for a complete component.

WORKMANSHIP

Defects and imperfections in glass may arise from many causes associated with melting, forming, finishing, and other operations. The term "workmanship" is used here to cover all such deficiencies.

Imperfect melting operations may result in solid or gaseous inclusions (stones, bubbles, etc.), and in homogeneities in the glass body (striae, cords, and sometimes, cloudiness). Forming operations can produce faulty shapes because of imperfect equipment, improper operation (including the use of unsuitable forming temperatures), and excessive ·· ·'ing of formed glass. The required dimensions may not be met, and the article may be distorted or warped (for example, waviness in a rolled plate or a drawn sheet). Surfaces may be rough and also irregular at the mold seams; in addition they may contain laps, checks or cracks, trapped air, and surface inclusions such as scale.

The finishing operation of grinding leaves the glass surface rough, pitted, and mechanically weak. Subsequent polishing may not completely remove these imperfections. There are a number of surface defects which result from incomplete polishing and which may be classed generally under the term "short finish." Scratches and sleeks can be produced after all the grinding marks have been removed and laminating operations may produce defects at interfaces between glass and plastic.

Dimensional tolerances of various types, thicknesses, lengths, and diameters will be found in most specifications. The maintenance of these

tolerances constitutes one phase of workmanship. In certain optical components, such as windows, deviation from the parallelism of the two surfaces (called a "wedge") is important, so that tolerances for this condition must be included in specifications.

The magnitude of internal or residual stresses in the glass can be used to evaluate the quality of annealing or the degree of tempering. These stresses are commonly determined from the relative retardation of polarized light which is caused by the stresses. This retardation is measured with a polarimeter. In well-annealed glass which is to be used for optical components (see MIL-G-174), the maximum allowable retardation is specified as 10 millimicrons per centimeter of the path of light, or an internal stress of the order of 50 psi.

In the case of tempered glass for aircraft glazing (see MIL-G-25667), the retardations resulting from the tensile stress in the midplane of a reference sample of 1/4-inch plate glass are specified as follows: semitempered, 1,400 to 1,900 millimicrons per inch of path; fully tempered, not less than 2,800 millimicrons per inch of path. Corresponding values for other glass thicknesses are not indicated specifically.

FUNCTIONAL TESTS

Using the two bases just mentioned it is practicable to formulate specifications for some products. They will state explicitly the property requirements of all materials used in the product, and details of procedures used in treatment and fabrication, together with such controls which may be required to assure proper standards of workmanship. This method is used on products where adequate testing of the complete component or structure is difficult or impracticable.

The opposite approach in formulating a specification is to permit the supplier some latitude in his choice of materials and procedures, but to include a functional test or tests which represent

the requirements of the most severe service condition anticipated. If the product meets these tests, it is considered to have complied with the requirements of the specification. These tests are frequently made more severe than any service condition, in order to accelerate the test. Both experience and special testing may be necessary to correlate the test conditions with the functional requirements of the product. Actually, many specifications combine elements based on properties and workmanship with others based on functional tests.

The optical transmission of a laminated glass structure can be specified from absorption coefficients and refractive indexes determined for the several elements of the composite window. If, however, the specified transmittance must be retained after the exposure of the laminate to some deteriorating agent, such as ultraviolet radiations, compliance is much more readily determined from a functional test made after the window is exposed to the deteriorating agent.

Thermal endurance of glass components can be assured by using a glass of suitable thermal expansion characteristics and a proper standard of workmanship. While these two requirements are included in some specifications on gage glasses, a functional test for thermal shock is usually added. Samples of the glasses are heated to a definite temperature in an oven and are then quenched in a water bath or by a water spray. Fracture of the glass represents failure.

Laminated glass products for safety glazing (Z26.1, MIL-G-3787, MIL-G-25811) are given tests for "nonscatterable" characteristics. The glass is impacted with steel balls, steel darts, or shot bags. Although the glass may break, the fragments must be retained by the plastic interlayer, except in small specified areas surrounding the point of impact. For tempered glass fragments may separate, but the size of the individual piece is limited. These are functional tests.

For bullet-resisting windows the obvious functional test is its actual impact by a bullet. In MIL-G-5485 the bullet is to have a striking velocity of 2,700 ft/sec, while the obliquity of the path of the bullet with respect to the face of the window is specified in terms of the weight of the bullet and the weight of glass per square foot of window. Results which indicate failure of a specimen are outlined clearly in the specification.

Specification MIL-G-2697 for tempered port-lights is of considerable interest. Strength requirements of these lights are defined in terms of an edge-loading test (arrangement shown in Figure 24). This load is specified in pounds for each size, diameter, and thickness included in the schedule. Two test procedure are given, one for lots not greater than 100 pieces and the other for lots greater than 100 pieces. For the smaller lots the pieces tested are subjected to a proof load, and compliance is based on the number of failures. Pieces not injured by the test are accepted. This procedure employs the method of attributes. For the larger lots a sample of ten pieces or more is selected and the specimens are loaded to destruction. If the average breaking load is equal to or greater than a specified value, about 30 percent higher than the proof load for the first type of test, the lot is accepted. The inspection procedure used in this case is by the method of variables.

The requirements of products are so complex that considerable variety is found in the methods and forms used for specifications.

TABLE XI. SPECIFICATIONS AND STANDARDS ON GLASS

NUMBER	TITLE
Military	
MIL-G-174	Glass, Optical
MIL-I-742	Insulation Board, Thermal Fibrous Glass
MIL-G-479	Glass, Ground (For Ordnance Use)
MIL-G-1366	Glass, Window, Aerial Photographic
MIL-G-2695	Glasses, Gage, Round and Flat, Reflex, Under 125 Pounds Pressure
MIL-G-2697	Glasses, Portlight, Circular, Heat-treated
MIL-G-2857	Glass, Heat-treated, Glazing, Rectangular (for Bridge Windows)
MIL-G-2860	Glass, Sight, Flat, Clear, Borosilicate
MIL-I-3158	Insulation Tape, Electrical, Glass Fiber, Resin Filled, and Cord Fibrous Glass
MIL-G-3787	Glass, Laminated, Flat (Except Aircraft)
MIL-G-5485	Glass, Laminated, Flat, Bullet-Resistant

TABLE XI. SPECIFICATIONS AND STANDARDS ON GLASS (Cont.)

NUMBER	TITLE
MIL-G-8602	Glass, Laminated, Flat, Aircraft
MIL-C-10797	Cloth, Coated, Glass, Silicone Rubber Coated
MIL-F-12298	Fabric, Glass, Woven
MIL-G-14754	Glass, Ground, (For Use in Ammunition)
MIL-I-15475	Insulation Felt, Thermal, Fibrous Glass, Semirigid
MIL-M-15617	Mat, Fibrous Glass, For Reinforcing Plastics
MIL-I-16411	Insulation Felt, Thermal, Glass Fiber
MIL-I-17205	Insulation, Cloth and Tape, Electrical, Glass Fiber, Varnished
MIL-G-18498-R	Glass Set, Water Gage, Flat, Plain, High Pressure Steam, (Glass, Mica and Gaskets)
MIL-I-18746	Insulation Tape, Glass Fabric Polytetrafluoroethylene Coated
MIL-T-19292	Tape, Glass, Fiber, Asphalt and Oil Impregnated
MIL-C-19663	Cloth, Glass, Woven Roving, for Plastic Laminate
MIL-R-19907	Repair Kit, Glass Reinforced Plastic Laminate
MIL-C-20079	Cloth, Glass, Tape, Textile Glass and Thread, Glass
MIL-G-21729	Glass-Fiber Base Laminate, Epoxy Resin
MIL-I-22023	Insulation, Felt, Thermal and Sound Absorbing Felt, Fibrous Glass
MIL-I-22344	Insulation Pipe, Thermal Fibrous Glass
MIL-I-22444	Insulation Tape, Electrical Self Bonding, Silicone Rubber Treated Bias Weave or Sinusoidal Weave Glass. Cable Splicing. Naval Shipboard.
MIL-C-22787	Cloth, Coated, Glass, Vinyl Coated Fuel and Flame Resistant
MIL-I-24178	Insulation Tape, Electrical, Semi-Cured Thermosetting Resin Treated Glass, Armature Bonding, Naval Shipboard.
MIL-G-25667	Glass, Monolithic, Aircraft Glazing
MIL-G-25871	Glass, Laminated, Aircraft, Glazing
MIL-C-27347	Cloth, Coated, Glass, Aluminum Face, Silicone Rubber, Back
MIL-G-43349	Glass, X-ray Protective
MIL-G-46108(MR)	Armor, Transparent, Laminated, Glass-faced Plastic Composite
MIL-G-55636	Glass Cloth, Resin Pre-impregnated (B Stage) (For Multilayer Printed Wiring Boards)
MIL-R-60346	Roving, Glass, Fibrous, (For Filament Winding Applications)
MIL-C-82254	Cloth, Coated, Glass, Chloroprene Coated
Standards	
MS-36078	Glass Tubing, Round, Capillary
MS-36079	Glass Tubing, Round, Standard Wall

TABLE XI. SPECIFICATIONS AND STANDARDS ON GLASS (Cont.)

NUMBER	TITLE
MIL-STD-34	General Requirements For The Preparation of Drawings for Optical Elements and Optical Systems
MIL-STD-105	Sampling Procedures and Tables for Inspection by Attributes
MIL-STD-109	Quality Assurance Terms and Definitions
MIL-HDBK-141	Optical Design
MIL-STD-150	Photographic Lenses
MIL-STD-1241	Optical Terms and Definitions
Federal	
DD-G-451	Glass, Plate, Sheet, Figured, (Float, Flat, for Glazing, Corrugated, Mirrors, and other uses)
DD-G-476	Glass, Flat, Glazing (For) Transmitting not less than 25% of Ultraviolet, Radiation at Wave Length 302 Millimicrons
DD-G-491	Glass, Liquid Sight Indicator, Flat
DD-G-511	Glass Tubing, Round (Gage, Boiler)
DD-G-541	Glassware, Laboratory
DD-M-00411	Mirror, Glass
DD-M-411	Mirrors, Plate Glass, Framed (GSA - FSS)
DD-T-741	Tubing, Glass, (Laboratory Use)
HH-I-551	Insulation Block Pipe Covering and Boards, Thermal (Cellular Glass)
MMM-A-131	Adhesive, Glass-to-Metal, (For Bonding of Optical Elements)
FED. STD.-515/8	Safety Glazing Materials for Automotive Vehicles
FED. STD.-515/13	Glare Reduction Surfaces - Instrument Panel and Windshield Wipers for Automotive Vehicles
USA Standards Institute (USASI)	
Z26.1	Safety Glazing Materials for Glazing Motor Vehicles Operating on Land Highways
Z97.1	Performance Specifications and Methods of Test for Transparent Safety Glazing Materials Used in Buildings
American Society for Testing Materials (ASTM)	
Specifications for:	
C 552	Cellular Glass Block and Pipe Thermal Insulation
C 599	Glass Process Pipe and Fittings
D 879	Pin-Type Lime-Glass Insulators, Communication and Signal
E 211	Cover Glasses and Glass Slides for Use in Microscopy

TABLE XI. SPECIFICATIONS AND STANDARDS ON GLASS (Cont.)

NUMBER	TITLE
Methods of Test for:	
C 146	Chemical Analysis of Glass Sand
C 147	Internal Pressure Test on Glass Containers
C 148	Polariscopic Examination of Glass Containers
C 149	Thermal Shock Test on Glass Containers
C 158	Flexure Testing of Glass (Determination of Modulus of Rupture)
C 169	Chemical Analysis of Soda-Lime Glass
C 169–65T	Chemical Analysis of Soda-Lime Glass for Silicon Dioxide
C 224	Sampling Glass Containers
C 225	Chemical Attack, Resistance to, of Glass Containers
C 240	Testing Cellular Glass Insulating Blocks
C 336	Annealing Point and Strain Point of Glass
C 337	Linear Expansion, Average, of Glass
C 338	Softening Point of Glass
C 429	Sieve Analysis of Raw Materials for Glass Manufacture
C 598	Annealing Point and Strain Point of Glass by Beam Bending
D 578	Glass Yarns, Specification and Methods of Testing
D 579	Glass Fabrics, Woven, Specification and Methods of Test for
D 580	Glass Tapes, Woven, Specification and Methods of Test for
D 581	Glass Tubular Sleeving and Braids, Woven, Test and Tolerances for
D 886	Glass Yarn, Impregnation and Penetration of, with Insulating Varnish
E 165	Liquid Penetrant Inspection
E 211–65T	Cover Glasses, and Glass Slides for Use in Microscopy, Specification and Methods of Test for
Definitions of Terms Relating to:	
C 162	Glass and Glass Products
Tentative Method of:	
C 600	Thermal Shock Test on Glass Process Pipe
C 601	Pressure Test on Glass Process Pipe
Recommended Practice for:	
F 14	Making and Testing Reference Glass-Metal Bead Seal

Appendix A
Glossary

anneal: To prevent or remove objectionable stresses in glassware by controlled cooling from a suitable temperature. Also see text of Chapter 4.

annealing point: The temperature of a glass at which internal stresses are reduced to acceptable commercial limits in 15 minutes. The temperature corresponding to a viscosity of about 10^{13} poises.

batch: The raw materials, properly proportioned and mixed, for delivery to the furnace.

blister: An imperfection; a relatively large bubble or gaseous inclusion.

bushing: A liner in the orifice of any feeder for molten glass; for example, the orifice ring of a gob feeder; or the unit through which molten glass is drawn in making fibers.

check: An imperfection; a surface crack in a glass article.

chip: An imperfection due to breakage of a small fragment out of an otherwise regular surface.

continuous filament: See Fiber.

cord: An attenuated glassy inclusion possessing optical and other properties differing from those of the surrounding glass.

coupling agent: A special sizing material applied to glass surfaces, particularly to fibers, to promote adhesion between the glass and some resinous material.

crush: A lightly pitted area resulting in a dull grey appearance over the region.

cullet: Waste or broken glass, usually suitable as an addition to raw batch.

devitrification: Crystallization in glass.

dice: The more or less cubical fracture of highly prestressed glass.

digs: Deep, short scratches.

feeder: A mechanical device for regularly producing and delivering gobs to a forming unit.

fiber: An individual filament made by attenuating molten glass. A continuous filament is a glass fiber of great or indefinite length. A staple fiber is a glass fiber of relatively short length (generally less than 17 inches).

fictive temperature: Glass in a given state can be brought suddenly to a temperature at which its structure or configuration will reach equilibrium. This will be the fictive temperature.

figured glass: Flat glass having a pattern on one or both surfaces.

fill: The unit amount of batch charged into a tank or pot.

fining: The process by which the molten glass approaches freedom from undissolved gases.

fire cracks: Cracks in ware caused by local temperature shock.

float glass: Glass which has virtually plane and parallel surfaces formed by floating in a continuous ribbon of glass on the surface of a bath of molten metal in a controlled atmosphere.

forehearth: A section of a furnace, in one of several forms, from which glass is taken for forming.

fracture mirror: On the fracture surface, a smooth flat area surrounding the fracture origin.

glass: Glass is an inorganic product of fusion which has cooled to a rigid condition without crystallizing. Glass is typically hard and brittle, and has a conchoidal fracture. It may be colorless or colored, and transparent to opaque.

glass ceramic: A material melted and formed as a glass, then converted largely to a crystalline form by processes of controlled devitrification.

gob: (1) A portion of hot glass delivered by a feeder.
(2) A portion of hot glass gathered on a punty or pipe.

knot: An imperfection; an inhomogeneity in the form of a vitreous lump.

lampworking: Forming glass articles from tubing and cane by heating in a gas flame.

lap: (1) An imperfection; a fold in the surface of a glass article caused by incorrect flow during forming.
(2) A tool used for polishing glass.

lehr (leer): A long, tunnel-shaped oven for annealing glass by continuous passage.

lines: Fine cords or strings, usually on the surface of sheet glass.

liquidus temperature: The maximum temperature at which equilibrium exists between molten glass and its primary crystalline phase.

low reflectance coatings: Transparent coatings applied to glass surfaces to reduce the amount of light reflected. This reduction is caused by interference between two reflected beams.

mat (fibers): A layer of intertwined fibers bonded with some resinous material or other adhesive.

parison: A preliminary shape or blank from which a glass article is to be formed.

plate glass: Glass from which surface irregularities have been removed by grinding and polishing, so that the surfaces are plane (flat) and parallel.

plunger: The reciprocating metal part which forces glass into the contours of a mold, or which, in a blank mold, forms the initial cavity for subsequent blowing.

poise: A basic unit of viscosity expressed in C.G.S. units; dynes $\times$ cm^{-1} $\times$ sec^{-1}.

polarimeter: Apparatus for measuring the rotation of the plane of vibration of polarized light in optically active substances. For glass these measurements are used for determining differences of stress.

preform (fibers): The process whereby cut strands of roving are drawn by suction onto a shaped screen, sprayed with binder, and cured in an oven. Also, the article made by this process.

preloaded (fibers): Containing or combined with the full complement of resin before molding.

prestressed glass: Glass in which residual stresses have been developed by heat treatment (for example, tempering), chemical treatment, or other means.

ream: An area of inhomogeneous glass incorporated in the sheet, producing a wavy appearance.

roving (fibers): One or more staple-fiber slivers, with a very small amount of twist. An intermediate stage between sliver and yarn.

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rub: Abrasion of the glass surface which produces a frosted appearance. It differs from a scratch. Sometimes called a scuff.

sand holes: Small fractures in the surface of glass, produced by the rough grinding operation and which have not been removed by subsequent fine grinding. See Short Finish.

scratch: An imperfection; a surface mark caused by hard material with a sharp point or edge.

seal: A fusion joint or union between glass and glass or glass and metal.

seed: An extremely small gaseous intrusion in glass.

sheet glass: Transparent flat glass having glossy, fire-finished, apparently plane and smooth surfaces, but having a characteristic waviness of surface.

short finish: An imperfection in plate glass resulting from incomplete polishing.

size (fibers): Any coating applied to textile fibers during the forming operation.

skim: An imperfection; streaks of dense seed with accompanying small bubbles.

sleek: An imperfection; a fine scratch-like mark having smooth boundaries, usually produced by a foreign particle in the polishing operation.

smoke: Discoloration of glass caused by a reducing flame as when heated in open-fired lehrs.

softening point: The temperature at which a glass will deform under its own weight. The corresponding viscosity may vary from $10^{7.5}$ to $10^{8.5}$ poises, depending upon the density of the glass.

staple fiber: See fiber.

stone: An imperfection; crystalline contamination in glass.

strain point: The temperature of a glass at which internal stresses are reduced to an acceptable commercial limit in 4 hours. The temperature corresponding to a viscosity of about $10^{14.5}$ poises.

stria: An imperfection; a cord of low intensity of particular interest in optical glasses.

string: An imperfection; a straight or curved line, usually resulting from slow solution of a large grain of sand or foreign material.

tempered glass: Glass which has been prestressed by rapid cooling from a temperature near its softening point.

textile fibers: Fibers or filaments that can be processed into yarn or made into fabric by intertwining in a variety of methods, including weaving, knitting, and braiding.

thermal endurance: The relative ability of glassware to withstand thermal shock.

wave: Glass defects resulting from surface irregularities making objects viewed at varying angles appear wavy and bent.

weathering: Attack of a glass surface by atmospheric elements.

wedge: Departure of the two surfaces of flat glass from parallelism. Usually expressed in terms of minutes and seconds of arc or interference fringes per inch.

working point: Temperature of a glass corresponding to a viscosity of 10^4 poises, at which it may be suitable for some types of forming operations.

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