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DARCOM PAMPHLET

ENGINEERING DESIGN HANDBOOK

REDSTONE SCIENTIFIC INFORMATION CENTER



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DISCONTINUOUS FIBERGLASS REINFORCED THERMOPLASTICS

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DEPARTMENT OF THE ARMY
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ENGINEERING DESIGN HANDBOOK DISCONTINUOUS FIBERGLASS REINFORCED THERMOPLASTICS

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PREFACE

This handbook provides information related principally to families of thermoplastics reinforced with strand "E" glass. The handbook content, while limited to molding materials, advises the reader that other forms of thermoplastic materials—such as foams and elastomers—are also glass reinforced.

The wealth of detail and information presented will acquaint US Army Materiel Development and Readiness Command personnel with the range of available materials and their unique mechanical, electrical, and physical properties; fabrication processes, including joining, together with their advantages and disadvantages; and areas of glass-reinforced thermoplastics (GRTP) application. Thus potential uses of GRTP's—with their attendant lower cost and ease of production—are suggested for the design and procurement of Army materiel.

The handbook features the relationships between the GRTP's and their properties—the relationships are displayed both in tabular form and graphically. The influence of composite variables—volume of glass fiber; glass strand solids and bundle size; glass filament diameter, length, and orientation—on properties are similarly displayed.

Another unique feature of the handbook is the manner in which the polymers and their associated properties are presented. In one breakout, the GRTP's are displayed as the independent variable; in a second breakout, the properties are displayed as the independent variable.

The handbook was prepared by Ms. Joan B. Titus, Plastics Technical Evaluation Center (PLASTEC), the Defense Department's specialized information center on plastics, located at the US Army Armament Research and Development Command, Dover, NJ.

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CHAPTER 1

INTRODUCTION

Composites, glass fiber reinforced thermoplastics (GRTP), categories of resins, and fiberglass types and forms—E, C, and S glasses—are defined. Processes for making GRTP are described briefly. Some advantages and disadvantages associated with GRTP's are given.

1-1 DEFINITIONS

1-1.1 COMPOSITE

A composite is a material created by combination of two or more materials to achieve specific characteristics and properties superior to those exhibited by each component material alone.

1-1.2 FIBERGLASS REINFORCED PLASTICS (FRP)

Fiberglass reinforced plastics are families of composite materials. The performance of the composite material is dependent on and achieved by the selection and combination of three components: resin or matrix system, glass type and form, and process.

1-1.2.1 Resins

There are two categories of plastic resins:

1. *Thermosets.* Those materials that undergo an irreversible chemical polymerization (cure) reaction when heated.

2. *Thermoplastics.* Those materials that undergo no chemical change when heated, changing only in physical condition. The process of softening with heat and solidifying with cooling can be repeated.

1-1.2.2 Fiberglass Type and Form

Glass fibers are made from E, C, and S glasses.

“E” (Electrical) glass is the most commonly used glass. It provides superior electrical characteristics and high heat resistance—properties which are particularly suited for electrical insulation applications.

“C” (Chemical) glass has superior acid corrosive resistance. It is used for applications where such resistance is required, i.e., industrial batteries.

“S” (High Tensile Strength) glass is used in high performance structural applications.

Strength-to-weight ratios exceeding those of most metals can be reliably achieved.

“S-2” glass is a variant of “S”, but has the same glass batch composition. The sizing system is different, and a more rigid quality control is specified. S-2 glass is used in aerospace applications and in some electrical applications where higher tensile strength is required.

The various fiberglass forms are presented in Table 1-1.

TABLE 1-1. GLASS FIBER FORMS

Type	General Description
Strand	A primary bundle of continuous filaments combined in a single compact unit without twist
Roving or tow	A loose assemblage of continuous fibers formed into a single strand with very little twist
Chopped strand	Strands cut into short fibers
Reinforcing mat	Nonwoven random matting of chopped or continuous strands
Yarn	Strands of fibers or filaments in a form suitable for weaving
Surfacing and overlay mat	Nonreinforcing fibers in a random matting
Filament	A fiber characterized by extreme length
Woven fabric	Woven cloth

1-1.2.3 Processes

Fiberglass composites are processed by the following methods:

1. *Hand lay-up.* Fiberglass mat or fabric and resin are placed manually in a mold. Rollers compact the reinforcement and remove the air bubbles. Curing is at room temperature.

2. *Spray-up.* Resin and chopped fiber roving

are sprayed simultaneously on mold surface. The resulting mass is rolled, cured.

3. *Matched die molding preform and mat.* Reinforcement and resin are combined under heat and pressure. Mat reinforcements are used for relatively flat shapes. Complex parts require a preform.

4. *Filament winding.* Fiberglass strands or roving are wound in continuous lengths on a mandrel. Curing is at room temperature—in an oven or autoclave, or by bag or vacuum molding.

5. *Centrifugal casting.* Fiberglass reinforcement is placed in a hollow mandrel. The mandrel is rotated, and catalyzed resin is added.

6. *Continuous pultrusion* (extrusion). Impregnated glass reinforcements are pulled by tension through resin tank, machined dies, and onto racks, drums, or creels.

7. *Matched die molding preform.* A mixture of reinforcement resin, pigment, filler, release agent, and catalyst is inserted into a matched die press in bulk form. Heat and pressure are applied.

8. *Rotational molding.* A thermoplastic powder is used in this method to which glass reinforcements in the form of chopped strands are added. The resin powder and glass reinforcement are charged into a split hollow mold, heated, and biaxially rotated. After the material has fused, the mold is cooled, opened, and the part removed.

9. *Injection molding.* A mixture of short fibers and resin, either in precompounded pellet or loose powder form, is forced by a screw or plunger through an orifice into the heated cavity of a closed matched metal mold. This high volume process is the major method for forming glass-reinforced thermoplastics (GRTP) items.

10. *Solid-phase forming.* This is a deformation processing technology carried out on fiberglass reinforced sheets or billets at temperatures near but below the crystalline melting point on traditional metalworking equipment. Included are such fabrication techniques as forging, stamping, and drawing.

11. *Extrusion.* This is a process whereby resin and reinforcement are heated, mixed, and forced through a shaping orifice to become one continuously formed piece—usually sheet, rod, or pipe.

1-2 SCOPE

This handbook is limited to one category of fiberglass reinforced plastics, namely, discontinuous fiberglass reinforced thermoplastics—

i.e., the following families of thermoplastics reinforced with chopped strand “E” glass:

- Acetal
- Acrylonitrile Butadiene Styrene (ABS)
- Acrylic
- Cellulosics
- Ethylene Tetrafluoroethylene (ETFE)
- Ionomers
- Nylons (Polyamides)
- Polycarbonate
- Polyesters
- Polyethersulfone
- Polyethylene (PE)
- Polyphenylene Oxide (PPO)
- Polyphenylene Sulfide
- Polypropylene (PP)
- Polystyrene
- Polysulfone
- Polyurethane
- Polyvinyl Chloride (PVC)
- Styrene Acrylonitrile (SAN).

For the sake of brevity, this handbook is limited to molding materials only. However the reader is advised that other forms of thermoplastic materials, such as foams and elastomers, are also glass reinforced.

1-3 HISTORY OF GLASS-REINFORCED THERMOPLASTICS (GRTP)

The cornerstone of the GRTP industry was laid in the early 1950's under the direction of Rexford Bradt, founder of Fiberfil, Inc. In 1952, this company marketed a 30% glass-reinforced polystyrene molding compound which was used initially by the military to fabricate a nondetectable land mine. This first commercially available compound contained glass fibers 3/8 to 1 in. long. The long glass fiber compounds were designed for high performance applications.

Research concerning the phenomena and mechanisms of GRTP has been active since 1960. The material also received an impetus with the advent of the screw injection molding machine which aided in the dispersion of the fiberglass. In addition, short fiber formulations were developed to assist molders with plunger machines to obtain improved fiber dispersion. By 1967, 15 million pounds of GRTP compound were being injection molded per year. Production of GRTP increased to approximately 130 million pounds in 1973 and

135.5 in 1974 but fell to 115.5 million pounds in 1975 as a result of the turndown in the economy.^{1,2,3}

The characteristics of composites are being improved by several methods:

1. Existing resins are improved through chemical modification or alloys with other compatible resins.

2. New resin systems with unique properties (e.g., high temperature) are being developed.

3. Interfacial investigations are resulting in superior resin/glass bonding via appropriate coupling agents and optimum glass fiber lengths.

4. Improved processing techniques which reduce compound degradation and fiber attrition, and promote optimum glass fiber orientation.

GRTP's are used in two forms: a dry blend of resin and glass fibers, and glass-reinforced pellets. The most common material is a precombined and pelletized blend of polymer and 10-40% by weight glass fiber reinforcement. These compounds can then be formulated to desired glass-resin combinations via let-down (diluted) with virgin resin concentrated pellets. For the past five years the ratio of precompounded GRTP to custom mixed or dry blended at the machine has been 80% precompounded, 20% direct molded.

1-4 MECHANISM OF COMPOSITES

Glass-reinforced composites consist of high modulus, high strength filaments bonded together by a much softer matrix to form a high modulus, high strength material. The tensile strength of glass is increased from a few thousand pounds per square inch in the bulk to over 500,000 psi in virgin fibers and in some cases to about 1,000,000 psi. However, for these fibers to be useful, they must be combined with a matrix to protect the fiber surfaces, space the fiber, transfer stress to and between the fibers, and control crack propagation. Control of crack propagation is significant since it achieves fracture toughness in essentially brittle materials.

The toughness of composites, in addition to that imparted by the fiber strength, arises from two energy-absorbing mechanisms: (1) the energy absorbed in pulling fibers out of the matrix as the fibers separate under load; and (2) as the propagating cracks are deflected along with fiber-matrix interface, i.e., the energy absorbed as the resin is separated from the fiber by continuance of crack propagation.

Composite properties depend upon many variables such as fiber and matrix properties; sizing, volume content, orientation, and geometry of the fibers; and compounding and processing techniques. All of these are controllable and can be selected by the fabricator to fulfill the requirements of specific applications. Unlike ordinary materials, the properties of composites are anisotropic, i.e., varying with the axis of testing.

The mechanical properties of short fiber composites—assuming strong matrix-to-fiber adhesion—are determined primarily by fiber length, aspect ratio (l/d), and orientation. Stresses are transferred to individual fibers by interfacial shear stresses, as shown in Fig. 1-1, for tensile stress applied axially relative to fiber orientation. The extent to which these stresses can be transferred to the fiber depends on the area of fiber surface bonded to the matrix as controlled by fiber length and fiber aspect ratio. Fig. 1-2 illustrates how a fiber of given diameter must exceed a critical length L_c if it is to function efficiently and carry maximum load. The critical length is the length necessary to pick up at fiber midpoint the stress that would be found on a similar fiber infinitely long. The portion of fiber which carries maximum load increases with the length of fiber exceeding the critical length; fiber efficiency increases accordingly.

Fiber efficiency for uniaxially oriented short fibers is defined as percentage effectiveness in providing reinforcing action relative to uniaxially oriented continuous fibers at the same volume percent loading. Experimental data normalized for fiber volume indicate fiber efficiency for modulus reinforcement is about 40% at a 50 aspect ratio, 60% at 100, and slowly increases to around 80% at 1000. Fiber efficiency for strength is about 50% at a 50 aspect ratio, 80% at 100, and then increases slowly to 85-90% at 1000 aspect ratio. Modulus values are predictable with good accuracy from theoretical treatments, but development of predictive capabilities for strength has proved more difficult. As a generalization, fibers



Figure 1-1. Representation of Origin of Shear Stresses on Short Fibers⁴

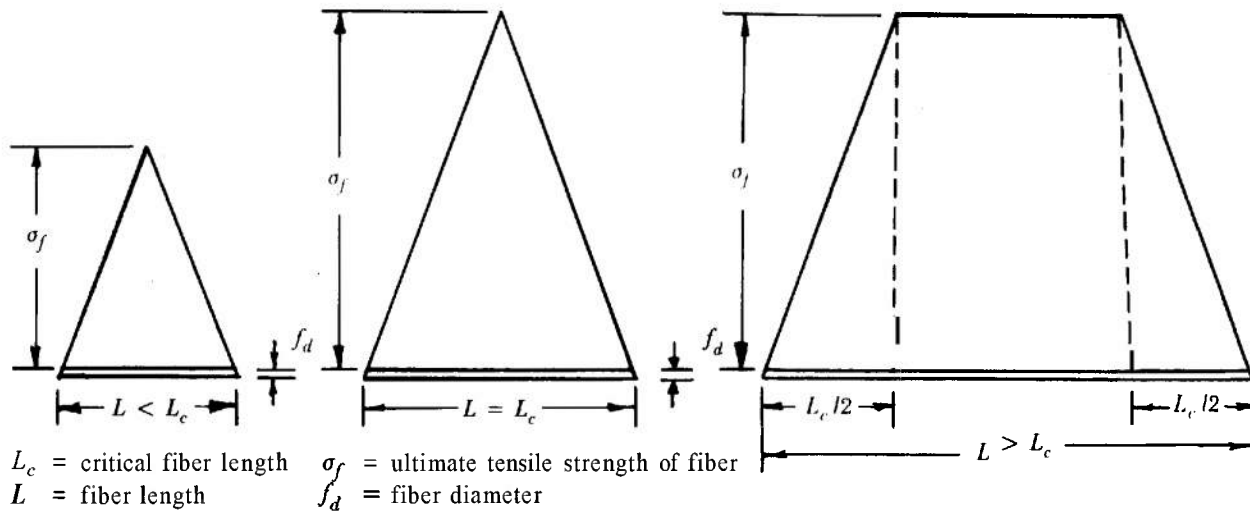


Figure 1-2. Representation of Build-Up of Tensile Stresses on Fibers

must have minimum aspect ratios in the range 50-100 to be useful.

1-5 PROPERTIES OF COMPOSITES

Virtually every thermoplastic material will receive some benefits from the incorporation of glass-fiber reinforcements. However, the improvements are more dramatic for some polymers than others (see Table 3-1).

Two properties which have variable response to glass reinforcement are notched Izod impact strength and heat distortion temperature (deformation under load). Generally, the notched Izod impact strength for rigid, brittle, or glassy polymers improves greatly while ductile, rubbery, tough polymers lose some of their energy-absorption characteristics with the addition of glass. In the case of heat distortion temperatures, polymers which are crystalline in nature have their heat-distortion points increased by 100-200 deg F. Amorphous polymers show a much smaller increase, usually about 20-30 deg F.

Specifically, the reinforcement of polymers with glass fibers substantially improves mechanical properties such as strength and stiffness; improves dimensional stability, mold shrinkage, and chemical resistance; and improves the dc electrical properties of dielectric strength and arc resistance as well as ac dielectric constant and dissipation factor. Both increases and decreases are noted in volume resistivities. Reinforcement also reduces percent elongation and thermal expansion properties.

The ability to mix thermoplastic resins and

glass reinforcements has expanded the selection of materials available, with a wide range of properties and prices, which can be used to fabricate finished parts.

1-6 PROCESSING GLASS-REINFORCED THERMOPLASTICS

GRTP products can be fabricated by injection molding, cold stamping, forging, thermoforming, rotational molding, and extrusion. The mode of fabrication is determined by part size, matrix selection, volume, and design complexity. GRTP's can be joined by adhesive bonding, fusion bonding (heat staking, spin welding, ultrasonic welding, and plastic rod welding), and mechanical fastening. Decorating, painting, and plating vary with the thermoplastic resin selected.

1-7 ADVANTAGES AND DISADVANTAGES OF GLASS-REINFORCED THERMOPLASTIC MATERIALS

GRTP's are in a period of dynamic growth. This family of engineering materials is competing with nonreinforced thermoplastics, thermosets, die castings, and sheet metal assemblies. Some of the advantages and disadvantages in selecting this material for a particular application are given in pars. 1-7.1 and 1-7.2.

1-7.1 ADVANTAGES

Advantages of GRTP materials are:

1. GRTP materials enable the designer to

select a specific composite to meet such needs as lubricity, paintability, detergent resistance, fire retardance, or weather resistance.

2. By varying fiber glass content, the designer can achieve different property values such as strength, rigidity, temperature resistance, thermal expansion, creep, and low temperature impact for a specific resin system.

3. Any shortage of a thermoplastic resin can be partially relieved since the composite contains 10-40% by weight of silica—a plentiful material.

4. GRTP composites significantly improve the property shortcomings of thermoplastic systems such as creep, low modulus, dimensional stability, mold shrinkage, low temperature impact, and high temperature stiffness loss.

5. The higher strength of GRTP composites often permits thinner parts, resulting in a material savings.

6. Electrical insulation is inherent in the glass fibers of GRTP composites, contributing to good dielectric properties.

7. GRTP composites exhibit superior chemical resistance compared to the neat (unreinforced) resins.

8. GRTP composites offer an improved cost-performance over engineering nonreinforced thermoplastics.

9. GRTP injection moldings usually offer labor savings over compression molded thermosets.

10. GRTP composites offer greater design flexibility than metals. Because of processing and close-tolerance molding improvements, multipart assemblies can often be combined into a single injection molded part. In such a part, the combination of bosses, studs, and molded-in inserts eliminates both assembly and machining operations.

11. GRTP's are easily injection molded—the most economical, most automated plastics production process for high volume applications.

12. Design flexibility allows a wide variety of assembly techniques for maximum strength.

1-7.2 DISADVANTAGES

Disadvantages of GRTP materials are:

1. Processing temperatures of GRTP's are normally 20-50 deg F higher than those of nonreinforced materials.

2. Machine wear in injection molding and extrusion is more significant in GRTP's due to the abrasiveness of the glass fibers and corrosiveness of fiber sizing materials.

3. The ambient notched impact strength of tough thermoplastics is generally reduced with glass reinforcements.

4. All GRTP's have anisotropic properties due to the alignment or orientation of the glass fibers during processing.

5. GRTP composites cannot be transparent due to the glass fiber fillers. They can be translucent, however.

6. There is usually a sacrifice in surface gloss finishes of GRTP composites over the nonreinforced material.

7. In general, glass-reinforced materials tend to be more expensive than nonreinforced materials.

8. Reinforcements and fillers increase the specific gravity of the material.

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CHAPTER 2

GLASS FIBER REINFORCEMENT

The characteristics of glass fibers, as they affect the physical and mechanical properties of polymers into which they are incorporated, are treated in detail. Physical, mechanical, electrical, thermal, acoustical, and optical properties and the chemical composition of E, C, and S glasses are listed. Treatment of the glasses to improve their engineering properties and facilitate strand handling and processing is described. Theory relative to the mechanics of how the glass fibers improve the physical properties of the polymers is presented. The effects of composite variables—volume of glass fiber, glass strand solids, glass strand bundle size, glass filament diameter, glass fiber length, and glass fiber orientation—along with the influence of the chemical and physical properties of the polymer matrix—are discussed. The effects of processing and compounding on the properties of the resulting GRTP are discussed. The relationships between the various parameters discussed are shown in tabular and graphic form.

2-1 INTRODUCTION

Glass has been one of man's most useful materials for centuries. However, the properties of glass filaments were not recognized until about 50 yr ago. In fact, glass filaments were not commercially available until about 1938. They have only been used in the thermoplastic industry for the last 15 yr with much of the growth occurring in the last 10 yr. Today, glass fibers are produced by several major suppliers: Owens Corning Fiberglas Corporation, Pittsburgh Plate Glass, Johns Manville, and Certain-Teed Products Corporation.

There are several innate characteristics of glass fibers which make them ideal for plastic reinforcements. They are:

1. Elasticity. Glass fibers obey Hooke's Law. Typical fibers have a maximum elongation-at-break of 5%.

2. Good thermal properties. Glass fibers are not combustible, and have a low coefficient of thermal expansion and a high thermal conductivity. They can retain approximately 50% of their strength at 700° F and 25% at 1000° F.

3. Dimensional stability.

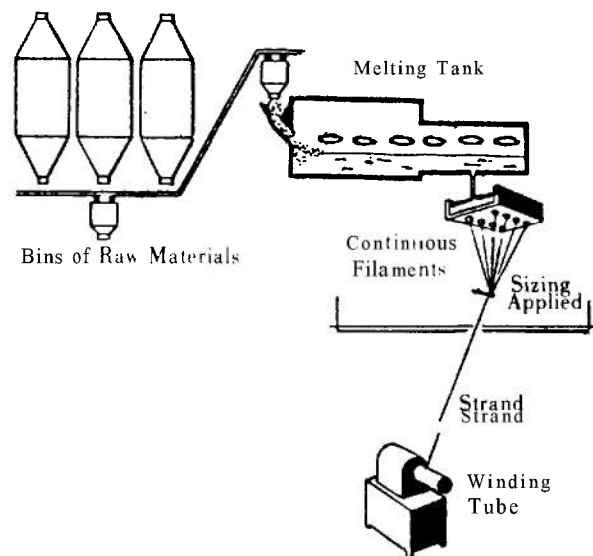
4. Excellent chemical and moisture resistance. Glass fibers do not absorb moisture, rot, or mildew; and resist all solvents, and most acids and alkalis.

5. Excellent electrical properties. Glass fibers have high dielectric strengths and low dielectric constants.

6. Lastly, they present a high performance reinforcement at relatively low cost.

Glass filaments are produced by forcing the raw glass in the form of marbles through a

bushing containing 204 orifices (see Fig. 2-1). Just below the bushing, the cooled filaments are protected by the application of starch-oil sizing. The sizing performs three functions: (1) it prevents the filaments from abrading one another, (2) it lubricates the filaments so they can move relative to one another, and (3) it provides a compatible interface between the glass filaments and the thermoplastic matrix they reinforce. After sizing, the untwisted filaments are gathered into a bundle or strand on a rotating drum.



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Figure 2-1. Commercial Process of Forming Continuous Glass Fibers²⁸

Commercial glass fiber reinforcements are produced in a variety of forms: continuous strand, rovings, chopped strands, mats, fabrics, and woven rovings. For the purpose of this handbook, only chopped roving and strand are of interest. The term continuous strand roving refers to a collection of parallel strands (ends) or filaments assembled without twist on a cylindrical tube. Continuous strand rovings are available in a variety of number of ends or yields. Yield is the number of yards per pound. (Typical rovings contain 60 ends of strands and have a length of 224 yd/lb.)

Rovings are rated by the following characteristics:

1. Tensile Strength. Determined by the glass composition and influenced by the efficiency of the sizing material
2. Strand Integrity. The degree of bonding between the filaments in the individual strands (ends)
3. Ribbonization. The degree to which the strands are held together in the roving
4. Catenary. The degree of sag between the individual strands in the roving
5. Wet Out. The speed and degree to which the roving is wet by the thermoplastic matrix

6. Choppability. The ease of chopping into short lengths, retention of strand integrity, and the amount of static electricity produced by the roving when it is further processed into chopped strands.

Continuous roving or strand is chopped into short lengths 1/8 to 2 in. for reinforcing thermoplastics. Chopping is done by the glass supplier or the user.

Chopped strands are available with different sizing for compatibility with various thermoplastic resin systems. Table 2-1 lists the recommended reinforcements for specific thermoplastic resins.

The factors affecting the properties of the reinforced thermoplastics are type of glass reinforcement, sizing, interface between glass fiber and plastic matrix, fiber dispersion, fiber concentration, fiber orientation, and fiber length and diameter. These factors are discussed in the paragraphs that follow.

2-2 TYPES OF GLASS FIBER REINFORCEMENTS

Various types of glasses are commercially available. They have been developed to provide

TABLE 2-1. GLASS FIBER REINFORCEMENTS FOR THERMOPLASTICS

Thermoplastic Resin	Glass Fiber Reinforcement Manufacturers' Designation		
	Owens Corning Fiberglas	Pittsburgh Plate Glass	Johns Manville
Acetal Homopolymer	409	3530	---
Acetal Copolymer	847, 409	----	---
Acrylic (PMMA)	---	3260	---
Styrene (ABS)	414	3130	308
Modified Polyphenylene Oxide	497	3250	---
Nylon (all types)	411, 409	3530	704
Polyaryl Ether		3530	---
Polycarbonate	409	3260	704
Polyethylene	415, 432	3250	308
Polyphenylene Oxide	---	3530	---
Polypropylene	432, 885	3130, 3250	308
Polystyrene	413, 885, 414	3130	308
Polysulfone	497	3530	---
Polyurethane	409, 411	3530	---
Styrene Acrylonitrile	414, 885	3130	308

various levels of performance. Some of the glass types used in reinforced plastics are:

1. E Glass. A lime-alumina-borosilicate glass specifically designed for production of continuous fibers primarily for electrical applications. This glass has found a great variety of uses in reinforced plastic products. It constitutes the major portion of all continuous filament production and reinforcement of thermoplastics.

2. S and S-2 Glass. A high tensile strength

glass developed for aerospace and defense applications. This glass has a tensile strength approximately 33% greater than E glass and a modulus 20% greater. S-2 glass has the same basic glass composition as S glass but differs in sizing composition and quality control of raw materials.

3. D Glass. This is an improved dielectric glass developed for high performance electronic applications. Although the mechanical properties of

TABLE 2-2. TYPICAL PROPERTIES OF E, S, D, AND C GLASSES

Property	E Glass	S Glass	D Glass	C Glass
Physical Properties^a				
Specific gravity, dimensionless	2.54	2.49	2.16	2.49
Mechanical Properties^a				
Virgin tensile strength at 72°F, psi ^c	500,000	665,000	350,000	400,000
Yield strength at 1000°F, psi	120,000	275,000		
Ultimate strength at 1000°F, psi	250,000	350,000		
Modulus of elasticity at 72°F, psi	10,500,000	12,400,000	7,500,000	10,000,000
Modulus of elasticity at 72°F (after heat compaction), psi	12,400,000	13,500,000		
Modulus of elasticity at 1000°F (after heat compaction), psi	11,800,000	12,900,000		
Elastic elongation at 72°F, %	4.8	5.4	4.7	
Thermal Properties^b				
Coefficient of thermal expansion, in./in. • °F X 10 ⁻⁶	2.8	1.6	1.7	4.0
Specific heat at 75°F, Btu/lb • °F	0.192	0.176	0.175	
Softening point, °F	1,555	1,778	1,420	1,380
Strain point, °F	1,140	1,400	890	1,026
Annealing point, °F	1,215	1,490	970	1,090
Electrical Properties^b				
Dielectric constant at 72°F, 10 ⁶ Hz, dimensionless	5.80	4.53	3.56	6.24
Dielectric constant at 72°F, 10 ¹⁰ Hz, dimensionless	6.13	5.21	4.00	—
Loss tangent at 72°F, 10 ⁶ Hz, dimensionless	0.001	0.002	0.0005	0.0052
Loss tangent at 72°F, 10 ¹⁰ Hz, dimensionless	0.0039	0.0068	0.0026	
Acoustical Properties^a				
Velocity of sound (calculated), ft/s	17,500	19,200	16,000	—
Velocity of sound (measured), ft/s	18,000			
Optical Properties^b				
Index of refraction, dimensionless	1.547	1.523	1.47	—

^aProperties measured on glass fibers.

^bProperties measured on bulk glass.

^cTensile strength of glass fibers which have not contacted other gas, solid, or liquid materials and have been stored at ambient room temperature.

D glass are lower than E glass and S glass, its lower dielectric constant and lower density make it attractive for electronic applications.

4. C Glass. A glass developed to provide greater resistance to acids than E glass.

Representative properties and formulations of these glasses are given in Tables 2-2 and 2-3.

TABLE 2-3. TYPICAL E, C, AND S GLASS COMPOSITION'

E Glass		S Glass		C Glass	
Com-pound	Range Wt. %	Com-pound	Wt. %	Com-pound	Wt. %
SiO ₂	52-56	SiO ₂	65	SiO ₂	65.0
Al ₂ O ₃	12-16	Al ₂ O ₃	25	CaO	14.0
CaO	16-25	MgO	10	MgO	3.0
MgO	0-6			Na ₂ O	8.0
B ₂ O ₃	8-13			B ₂ O ₃	6.0
Na ₂ O &				Al ₂ O ₃	4.0
K ₂ O	0-3				
TiO ₂	0-0.4				
Fe ₂ O ₃	0.05-0.4				
F ₂	0-0.5				

2-3 GLASS SURFACE TREATMENT AND INTERFACE

Glass filaments in pristine form are friable and easily damaged. Therefore, it is the practice to "size" or surface treat them immediately (0.01s), after their attenuation from the melt, with a complex coating. This coating or "size" in chopped rovings consists of four components which are essential for glass fibers in the reinforcement of thermoplastics (as distinguished from textile fibers). These are a film-former, lubricant, antistatic, and coupling agent.

Other sizes are used which do not contain a coupling agent when glass filaments are to be plied or woven. This sizing is removed from the fabric or roving by burning in a hot air circulating oven, and a "finish" applied to the heat-cleaned surface. This surface treatment is similar to the one-time size used in chopped rovings and contains a compatible coupling agent.

The purposes of the film former are to bind the multifilament strand into an integral unit, protect the strand against abrasion, and provide enough frictional drag to allow winding for packaging. The function of the lubricant is to protect the strand against both internal and external abrasion. The antistatic agent dissipates the electrostatic charges induced by friction.

The most important component of the size is the coupling agent (coupling agents are discussed in par. 2-3.1). Its purpose is to ensure good adhesion between the organic matrixes and the inorganic glass reinforcements. Coupling agents play a critical role in determining the physical, mechanical, and electrical properties of composites.

In order to exploit the full capability of these reactive agents, many studies of the phenomena at the interface between the glass and matrix have been undertaken. Some of the studies and theories studied concerning the interface phenomena are listed in Table 2-4. These investigations are beyond the realm of this handbook, and the interested reader is referred to Ref. 2; the proceedings of the "Sessions on Interface" of the Society of Plastics, Inc., Reinforced

TABLE 2-4. THEORIES AND STUDIES OF THE INTERFACE

<u>Theories of Mechanisms at the Interface</u>
The Chemical Bonding Theory
Deformable Layer Theories
Preferential Adsorption Theory (modified from the Deformable Layer Theory)
Restrained Layer Theory
Coefficient of Friction Theory
Surface Wettability Theory
Reversible Hydrolyzable Bond Theory (combination of Chemical Bonding Theory, Restrained Layer Theory, and Deformable Layer Theory)
<u>Studies of Interface</u>
Fourier Transform Infrared Spectroscopy
Auger Spectroscopy
Raman Spectroscopy
Electron Micrographs of Composites
Optical Ellipsometry of Adsorbed Films on Glass Fibers
Radioisotope Studies of Coupling Agents
Characterization of Fundamental Micro-Mechanics Parameters

Plastics/Composite Institute; and the open literature.

A glass-fiber surface treatment does many things at the interface; all of which are important to different degrees. Irrespective of the various theories, a requirement for a high strength composite under loading conditions requires an effective transfer of stress in all parts of the composite from fiber to fiber across the resin-glass interface. Stress transfer also must be efficient under a wide variety of environmental conditions, often for long periods of time. Fiber treatments play a part in not only strengthening but maintaining this interfacial bond.

2-3.1 COUPLING AGENTS

The versatility and effectiveness of organo-functional silane coupling agents for the optimal reinforcement of thermoplastic matrixes to glass fibers have been recognized in the plastics industry for a decade. The generic formula of a silane coupling agent is $YRSiX_n$. The X units in this formula represent hydrolyzable groups bonded to silicon. These are usually chloro, alkoxy, or acetoxy groups. In the application of coupling agents from an aqueous solution, these groups hydrolyze to form silanols and HX . It is this portion of the coupling agent molecule,



the $-SiX_n$, or its reaction products, that provides adhesion to the inorganic phase of a composite.

The Y units of this formula represent a range of organo-functional moieties that are selected to adhere to the organic matrix of the composite. They are bonded to silicon in a hydrolytically and thermally stable manner.

Silane coupling agents improve adhesion between organic and inorganic phases of a composite by adhering to these components with different portions of the same molecule, thus bridging the interface².

2-3.1.1 Inorganic Reactivity

Considerable effort has been expended in attempts to elucidate the manner in which silane coupling agents provide adhesion to glass fibers. The following is a listing of proposed adhesion mechanisms or contributions to adhesion that silane coupling agents can make based on secondary evidence:

1. Cross-linked sheath around glass
2. Removal of water from glass surface
3. Physical adsorption to glass
4. Hydrogen bonding to glass
5. Covalent bonding to glass
6. Protection of glass: eliminate microcracks, prevent flaw generation, prevent corrosion, prevent water access.

It is possible that in a given instance two or more of these suggested mechanisms may contribute to the adhesion of the silane coupling agents to the fiberglass surface.

Since the $-SiX_n$ portion of the silane coupling agent is converted to $-Si(OH)_n + nHX$ by hydrolysis, it should follow that the specific X group should not significantly affect the performance of the coupling agent. This has been confirmed².

2-3.1.2 Organic Reactivity

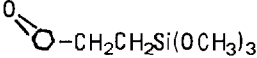
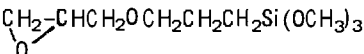
A number of mechanisms have been offered to explain the effectiveness of the silane coupling agents in improving the adhesion of silane-treated glass to the matrix resin. They are:

1. Improve resin wetting
2. Increase surface roughness
3. Stress-transferring boundary layer
4. Water barrier
5. Improve "compatibility" or diffusional bonding
6. Covalent bonding.

While any one or more of these mechanisms can contribute to improved adhesion in a specific instance, the establishment of covalent bonding between the organo-functional group on silicon and the matrix resin is believed to be the controlling factor in developing and maintaining good adhesion. The importance of selecting a silane coupling agent that is capable of efficiently reacting with the matrix has been well-established².

The choice of the organo-functional group is of critical importance in achieving the maximum strength of a reinforced composite. The number and type of thermoplastic matrix resins currently used require a range of coupling agent reactivity, and the number of commercially available coupling agents has grown to meet this need. Table 2-5 lists some of the commercially available silane coupling agents. In addition to these commercial materials, new silanes are continuing to be synthesized and evaluated to meet the needs generated by the introduction of new matrix resin systems.

TABLE 2-5. COMMERCIALY AVAILABLE SILANE COUPLING AGENTS²

Silane Identification*	Nomenclature	Structure	End-Use Polymers
A-151	Vinyltriethoxysilane	$\text{CH}_2=\text{CHSi}(\text{OC}_2\text{H}_5)_3$	
A-172	Vinyl-tris(2-methoxyethoxy)silane	$\text{CH}_2=\text{CHSi}(\text{OCH}_2\text{CH}_2\text{OCH}_3)_3$	polyethylene and and polypropylene
A-174	γ -Methacryloxypropyltrimethoxysilane	$\begin{array}{c} \text{CH}_3\text{O} \\ \\ \text{CH}_2=\text{C}-\text{C}-\text{OCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3 \\ \end{array}$	
A-1100	7-Aminopropyltriethoxysilane	$\text{NH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OC}_2\text{H}_5)_3$	
A-1120	N- β -(Aminoethyl- γ -aminopropyl)-trimethoxysilane	$\text{NH}_2\text{CH}_2\text{CH}_2\text{NHCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$	polyamide and polycarbonate
A-186	<i>p</i> -(3,4-Epoxy cyclohexyl)ethyl-trimethoxysilane		
A-187	γ -Glycidoxypropyltrimethoxysilane		polyvinylchloride
A-189	γ -Mercaptopropyltrimethoxysilane	$\text{HSCH}_2\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$	polysulfides and polyvinylchloride
A-16	Amyltriethoxysilane	$\text{CH}_3(\text{CH}_2)_5\text{Si}(\text{OC}_2\text{H}_5)_3$	

*Commercial designations of Union Carbide Corporation.

2-3.1.3 Improved Coupling Agents for GRTP's

Considerable effort has been expended to develop superior sizes to improve the engineering properties of GRTP's, and to facilitate strand handling and processing. Several examples of recent work are presented in the paragraphs that follow.

Marsden and Pepe³ have developed dual-purpose coupling agents: a lubricant modified silane and a film-forming polyamide. These sizes act as processing aids by reducing abrasional attrition or improving strand integrity. This results in strands with superior reinforcing ability. As coupling agents they also perform with increased potency relative to monomeric silanes such as A-1100.

Tables 2-6 through 2-9 show the increase in physical properties and impact strength of these sizes over the monomeric silane A-1100 in nylon 6/6 and polyester PBT reinforced with 30%, 0.25-in. chopped glass. In addition, these sizes pro-

vide improved strand processability and bulk properties to the chopped fibers. Bulk density — i.e., the volume occupied by a given weight of chopped strand — often is taken as an indication of the processability of fiberglass sizes. Strands of low bulk density tend to separate into the individual filaments (poor integrity), indicating a breakdown in the cohesive action of the size. This leads to serious processing, handling, and production problems. The bulk densities of lubricant silanes are compared in Table 2-10 with those of A-1100 and two commercial products known for their outstanding processing characteristics.

Silylated polyamides (Si-PAA's) are water-soluble polymers. Therefore, they are absorbed more evenly from a one-phase aqueous medium to form a continuous fiber coating. Such a size provides excellent strand integrity and stiffness, resin compatibility and, most importantly, chemical reactivity with glass through pending silane functionality.

These data show that for nylon 6/6 a simple

TABLE 2-6. EFFECT OF LUBRICANT-MODIFIED AMINOSILANE SIZES ON PHYSICAL PROPERTIES³

Glass Size ^a	Flex. Str., psi	Flex. Mod., psi x 10 ⁶	Tensile Str., psi	Tensile Str., Ret. ^b , %	HDT ^c , °F
30% GR Zytel 101 Nylon 6/6					
A-1100	34,100	9.9	20,800	60	489
Y-9072	36,700	10.2	24,000	60	495
Commercial (average) ^d	33,700	10.0	22,000	68	497
30% GR Valox 310 PBT Polyester					
A-1100	25,100	10.7	15,600	—	410
Y-9072	26,000	11.0	17,100	—	415
Y-9160	25,200	10.2	16,600	—	410
Y-9161	27,400	10.2	17,700	—	415
Y-9162	26,900	10.7	17,300	—	417
Y-9163	25,600	11.1	16,700	—	408
Commercial (average) ^d	29,500	11.6	18,600	—	415
30% GR Celanex PBT Polyester					
A-1100	23,600	10.5	14,200	—	405
Y-9072	26,100	10.6	16,000	—	417
Commercial (average) ^d	29,400	11.0	18,700	—	424

^aA-1100 monomeric silane; Y-9160, Y-9161, Y-9162, Y-9163, and Y-9072 lubricant-modified aminosilanes

^bAfter 24-h boil

^cAt 264 psi

^dAverage of three recommended commercial chopped strands

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monomeric coupling agent (A-1100) generates improvements of over 40% in flexural and tensile strength over that of bare glass while the modulus and heat distortion improve to a lesser extent. Also, a nonsilylated polyazamide (Y-5870) shows equivalent performance to A-1100 except for the lower wet-strength retention characteristic of nonsilane compounds. The silylation of the PAA backbone (Y-5986, Y-5987) yields substantial strength advantages of over 40% compared to Y-5870. Lastly, the heat deflection (HDT) temperatures are largely unaffected by changes in composite strength. This is in agreement with observations already made for other glass-reinforced engineering composites³.

A similar order of reactivity for A-1100 aminosilane, Y-5870, Y-5986, and Y-5987 was found in 30% glass-reinforced Vestamide-type nylon 12 previously summarized.

TABLE 2-7. IZOD IMPACT STRENGTHS OF LUBRICANT MODIFIED AMINOSILANE SIZE³

Glass Size	Notched, ft•lb/in. of notch		Unnotched, ft•lb/in. of width	
	Celanex	Valox	Celanex	Valox
30% GR Polyester PBT				
A-1100	0.9	0.8	7.5	5.7
Y-9072	1.4	1.6	10.8	9.1
Commercial (average) ^a	2.1	2.3	13.1	13.2
30% GR Nylon 6/6				
A-1100	1.7		7.5	
Y-9072	2.4		12.1	
Commercial (average) ^a	2.8		9.7	

^aAverage of three commercial glasses

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TABLE 2-8. EFFECT OF SILYLATED POLYAZAMIDE SIZES ON PHYSICAL PROPERTIES³

Glass Size ^a	Flex. Str., psi	Flex. Mod., psi x 10 ⁶	Tensile Str., psi	Tensile Str., Ret. ^b , %	HDT ^c , "F
30%GR Nylon 6/6					
None	17,100	8.1	10,000	86	459
A-1100	24,900	7.7	14,800	99	498
Y-5870	22,300	9.7	14,800	74	486
Y-5986	31,800	10.2	21,700	81	482
Y-5987	28,300	10.1	18,700	86	489
Commercial (average) ^d	30,800	9.3	21,400	88	492
30%GR Nylon 12					
A-1100	13,700	4.9	8,700	83	320
Y-5870	11,900	5.3	7,700	69	280
Y-5986	14,300	5.6	9,700	85	324
Y-5987	18,800	6.0	11,600	86	325
Commercial (average) ^d	14,600	5.1	9,700	94	331
30%GR Polyester PBT					
A-1100	22,200	1.0	13,200	—	399
Y-5922	22,200	1.1	14,100	—	410
Y-5923	24,800	1.1	15,800	—	419
Y-5986	24,200	1.1	16,000	—	424
Y-5987	20,900	1.1	13,000	—	421
Commercial (average) ^d	28,200	1.1	18,200	—	416

^aA-1100 monomeric silane, Y-5922, Y-5923, Y-5986, Y-5987, Y-8970 silylated polyazamides

^bAfter 16 h in 50°C water

^cAt 264 psi

^dAverage of three recommended commercial chopped strands

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TABLE 2-9. EFFECT OF SILYLATED POLYAZAMIDE SIZES ON IMPACT STRENGTH OF 30% GR PBT POLYESTER³

Glass Size	Notched, ft·lb/in. of notch	Unnotched, ft·lb/in. of width
A-1100	0.8	5.7
Y-5922	1.5	9.3
Y-5923	1.8	9.8
Y-5986	1.6	9.4
Y-5987	0.9	5.9
Commercial (average) ^a	2.3	13.2

TABLE 2-10. COMPARISON OF BULK DENSITIES OF LUBRICANT SILANES³

Size	Bulk Density, g/ml
A-1100	0.25
Y-9072	0.40
Y-9161	0.42
Y-9162	0.48
Commercial A	0.31
Commercial B	0.40
(all 0.25 in.)	

^aAverage of three recommended commercial chopped strands

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Four types of Si-PAA's were evaluated in 30% GR Valox-type PBT polyester. Aside from producing chopped strand with outstanding bundle integrity, the polyazamides generally outperformed A-1100 aminosilane in strength and thermal properties. Also, except for Y-5987, the polyazamides clearly outdistance the monomeric coupler in Izod impact strength.

Although these data establish the usefulness of silylated polyazamide sizes compared to conventional silanes, they also point out the limitations of such systems relative to commercial sizes. In the case of reinforced PBT, neither simple silane sizes—lubricant-modified nor polyazamides—can compete effectively with the sophisticated chemistry of modern commercial sizes either on strength or on impact and environmental resistance grounds.

Hartlein⁴ reported that the lack of correlation between thermoplastic laminates and injection-molded composites was due to the drastically different molding conditions rather than interference from sizing components. To obtain high strength GRTP composites, the glass coating should be of high modulus, be nonmelting, and be chemically adhered to the glass fiber surface. This coating must present a surface chemically similar to the matrix resin or at least one to which the matrix resin adheres tenaciously. Optimum results in this study were obtained with the following glass-reinforcement systems:

1. Polystyrene—Glass coated with an epoxy resin along with an amino or epoxy functional silane.
2. Nylon—A sizing based on a new polyaminosilane 2-6050 (polyaminotrimethoxsilane).
3. Polypropylene—Glass fibers coated with an

amino silane, i.e., 2-6020 or 2-6050 and $H_2C_8Cl_8$, dispersed on talc and dry blended with the glass fibers and thermoplastic powder.

Some property results are given in Tables 2-11 and 2-12.

A novel family of heat-induced adhesion promoters, the silyl peroxides, has been discovered and reported by Fan and Shaw.⁵ They are capable of promoting adhesion between a wide range of polymers and reinforcements. They wet the surface of most organic and inorganic materials. Adhesion increases with increasing extent of decomposition of the silyl peroxides. Their findings strongly suggest that a radical mechanism is involved, and covalent bond formation promoted by the silyl peroxide molecules is chiefly responsible for the adhesion. The silyl peroxides have proven to be excellent coupling agents for composite materials and versatile adhesion promoters for both organic and inorganic materials. Some results of polypropylene and polyethylene composite properties are given in Table 2-13.

The work described in Ref. 6 concerns the use of a poly(ethyleneacrylic acid) copolymer (Union Carbide EAA-9300) and gamma-aminopropyltriethoxysilane (Union Carbide A-1100) in combination as a size for fiberglass used to reinforce polypropylene and polyethylene.

Fiberglass sized with a combination of EAA-9300 and A-1100 produces composites having significantly higher flexural, tensile, and impact strengths and higher heat distortion temperatures than glass sized with EAA-9300 alone or with commercial glasses. These higher strength composites were fabricated by extruder compounding and by direct feed injection molding.

TABLE 2-11. INJECTION MOLDED 25% GLASS/
POLYSTYRENE (THERMOSETTING SIZINGS)⁴

Glass Treatment	Flexural Strength, psi	Notched Izod Impact, ft·lb/in.
No glass	12,800	0.3
25% Untreated Glass	17,200	0.9
Z-6020 ^a	16,600	1.2
Epoxy (DER 331)	17,800	1.1
2-6020 + Epoxy	21,800	2.0
2-6020 + Phenolic	20,600	1.9

^aDow Corning silanes

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TABLE 2-12. THERMOSETTING SIZES WITH
SAN/25% GLASS⁴

	Percent Strength Increase Due to Size	
	Tensile, %	Impact, %
Z-6040 ^a	9	0
Z-6040 (Epoxy)	32	130
Z-6040 (Epoxy Novalac)	40	160
Commercial	19	30

^aDow Corning silanes

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TABLE 2-13. PHYSICAL PROPERTIES OF INJECTION MOLDED GLASS-REINFORCED POLYPROPYLENE^a AND POLYETHYLENE^b WITH 30% WT. OCF-885, 0.25-in. CHOPPED FIBERGLASS

Silyl Peroxide		Polypropylene			Polyethylene		
Type	% by Wt	Flexural Strength, psi	Modulus of Elasticity, psi × 10 ⁵	Heat Distortion Temperature, 264 psi, °C	Flexural Strength, psi	Modulus of Elasticity, psi × 10 ⁵	Heat Distortion Temperature 264 psi, °C
Control		11,200	7.8	136	7,300	6.4	93
Vinyltris(t-butylperoxy)silane ^c	0.3	13,500	8.3	155	—	—	—
Tetrakis(t-butylperoxy)silane ^d	0.35	—	—	—	9,800	1.2	129

^aShell 5520

^bUCC DMD-7000 high density polyethylene

^cSilyl peroxide was put on the fiberglass before mixing with polypropylene

^dSilyl peroxide was not compounded into polyethylene

Size mixtures based on EAA-9300 and A-1100 are easy to formulate, water dispersible, and have stability and handling characteristics compatible with current sizing technology requirements.

This size system is not considered a finished package that satisfies all of the requirements for a polyolefin compatible reinforcement but as a novel approach that is easy to formulate, practical to use, and provides promising improvements in composite strength levels. Some results are given in Table 2-14.

Details of this and other work on surface treatment are given in Refs. 1-12 and the open literature.

2-4 MECHANICS OF LOAD TRANSFER AT THE INTERFACE

The load transfer mechanics at the fiber-matrix interface have been extensively investigated and reported on. Their significance in composite structural integrity can be understood when 1 in.³ of 50% volume glass fiber composite with a fiber diameter of 0.0003 in. contains approximately 6500 in.² of interface area².

As with surface treatments, this field of investigation is too complex to treat in detail in this handbook. However, a few highlights of the studies and theories are reported. The interested reader is again referred to the proceedings of the Society of Plastics Industry's Reinforced

Plastics/Composite Division and the open literature for more comprehensive information.

There are, in general, five assumptions underlying all the mechanistic interface theoretical studies, namely: (1) elastic constituent material behavior, (2) zero thickness for the interface, (3) perfect bond, (4) identical constituent bulk and in situ properties, and (5) a regular or repeating array of fibers. It is known that actual composites violate most, if not all, of these assumptions. However, the theoretical predictions still are an invaluable tool in identifying important local geometry and material variables, and in obtaining quantitative estimates of the stress state at the interface².

2-4.1 MECHANISTIC MODELS FOR LOAD TRANSFER AT THE INTERFACE

A mechanistic representation of load transfer from the matrix to the fiber in a short-fiber composite is illustrated in Fig. 2-2. Shown are the deformation pattern, the shear and axial stress distributions for elastic load transfer, and the shear and axial stress distributions for the inelastic case. There are three points of interest in Fig. 2-2, i.e.,

1. The shear stress at the interface increases rapidly to a peak value and then decays rapidly away from the fiber end.

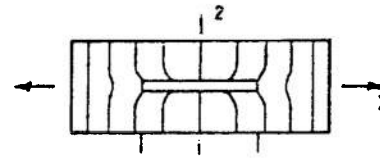
2. The axial stress in the fiber increases rapidly to its average value, the value the fiber attains

TABLE 2-14. INJECTION MOLDED POLYOLEFIN COMPOSITES—LABORATORY TREATED GLASS

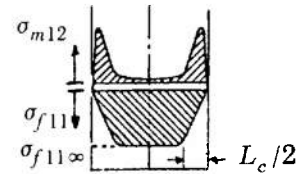
Properties	30 Wt. % 0.25-in. Glass—70 Wt. % Polypropylene				30 Wt. % 0.25-in. Glass—70 Wt. % High Density Polyethylene				
	0.8 Wt. % Binder Solids		1.6 Wt. % Binder Solids		0.9 Wt. % Binder Solids		1.6 Wt. % Binder Solids		
	EAA-9300/ A-1100 ^a	Commercial Control ^b	EAA-9300/ A-1100 ^a	Commercial Control ^b	EAA-9300/ A-1100 ^a	Commercial Control ^b	EAA-9300/ A-1100 ^a	Commercial Control ^b	
Flexural Strength, psi	9,000	11,000	8,400	13,000	11,000	11,000	11,000	12,000	8,400
Tensile Strength, psi	6,400	7,800	6,700	9,100	8,700	7,600	10,000	9,000	5,900
Izod Impact, ft•lb/in. notch	2.7	1.4	3.2	2.0	3.2	2.0	2.7	2.2	1.5
Heat Deflection at 264 psi, °C	119	147	121	146	129	123	125	124	103

^a A-1100/CO₂H molar ratio 1.0.

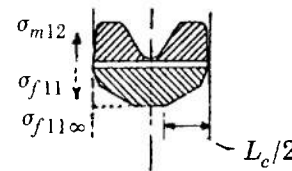
^b Commercially available chopped strand recommended for polyolefin resins.



(A) Deformation Model



(B) Stress Distribution at Interface Produced by Elastic Matrix



(C) Stress Distribution at Interface Produced by Inelastic Matrix

- σ_{m12} = interfacial shear stress
- σ_{f11} = fiber tensile strength
- L_c = critical fiber length

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Figure 2-2. Mechanistic Representation of Load Transfer at Interface²

in the composite, and remains constant for the elastic case.

3. The shear stress at the interface for the inelastic case increases to a value that will cause the interface to behave inelastically (plastically). The shear stress will stay at this value for some distance along the fiber until the greater portion of the load has been transferred to the fiber, and then it will decay rapidly².

The physical concepts fundamental in constructing theories for predicting the load transfer through the interface are illustrated in another mechanistic model in Fig. 2-3. The following are noteworthy :

1. The shear goes in one direction from one end of the fiber and reverses direction at the other end.

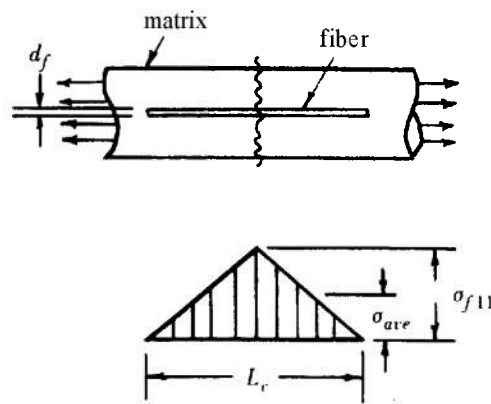
2. Shear stress reaches a maximum near the end of the fiber.

3. Shear stress decreases rapidly to zero along the fiber length where the normal stress in the fiber has achieved its composite average value.

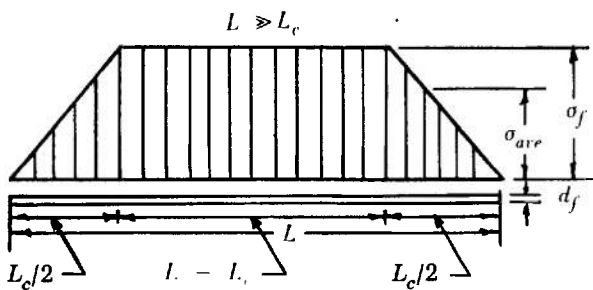
4. The interfacial shear stress increases gradually at first near the end of the fiber and then rapidly reaches its peak value at the end of the fiber.

2-4.2 METHODS FOR MEASURING INTERFACIAL BOND STRENGTH

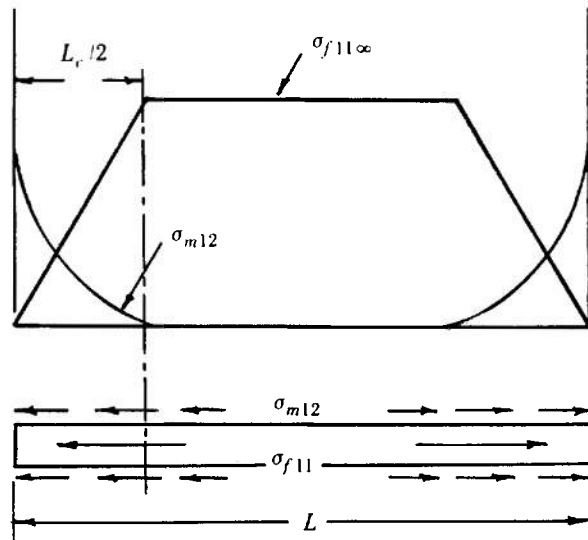
There are two types of methods to measure the stress state and the strength of the bond at the interface. One type concerns direct measurements involving model studies with either single or multifibers in a matrix casting. The other type involves indirect measurement of the bond



(A) Stress Distribution in Fiber of Critical Length
 $L_c d_f = (\sigma_{f11} / \sigma_{m12}) / 2$



(B) Fiber of Much Greater Than Critical Length



(C) Stress Distribution Within and on Surface of Fiber

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Figure 2-3. Schematic Illustrating Stress Distribution and Term Definitions at the Interface²

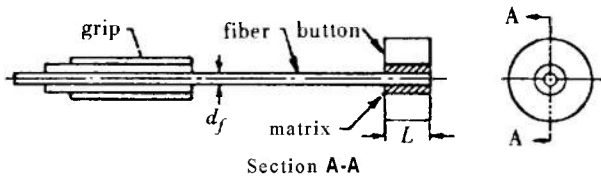
strength at the interface and can be both a qualitative and/or quantitative test.

A popular and easy test to measure bond strength is the fiber pullout strength test or button test as shown in Fig. 2-4. In this test, tensile failure denotes fiber breaks; shear failure denotes fiber pullout from the matrix. A critical fiber length can be determined in a plot of shear failure and tensile failure points by dropping a straight line through the intersecting points. This point defines the critical length of the fiber. The critical length is that fiber length that is required for the fiber to develop its fully stressed condition in the matrix.

Another method used to measure the bond strength at the interface is presented in Fig. 2-5. The force required to push a disk of the matrix along the fiber is plotted as a function of the crosshead movement. The mechanisms in this test demonstrate that the interface has at least two modes of transferring the load from the matrix to the fiber. The first is the bond strength that exists at the interface, shown by the bond peak in Fig. 2-5. The second is the friction force. How much each of these forces contributes or to what extent the friction force assists in transferring the load through the interface is still controversial.

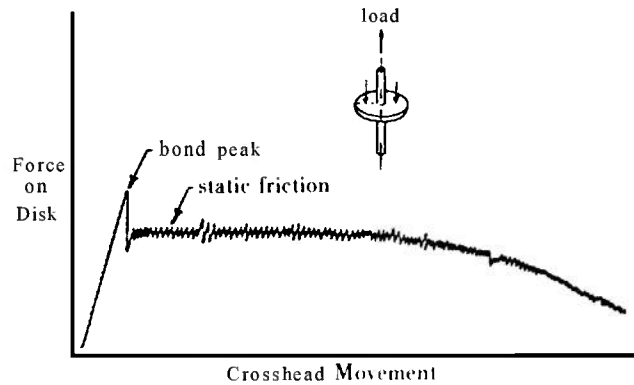
Fig. 2-6 illustrates another direct measurement model used to obtain shear and tensile strengths at the interface. The model for the bond shear strength at the end of the fiber is the one that has a constant cross section (Fig. 2-6(A)), while the model for the tensile strength is the necked-down specimen (Fig. 2-6(B)).

Indirect methods to measure the interface bond strength include the interlaminar shear strength test and the transverse strength test. A properly designed flex test with fibers parallel to the beam's longitudinal axis is another sensitive



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Figure 2-4. Schematic of Fiber Pullout Test Method²



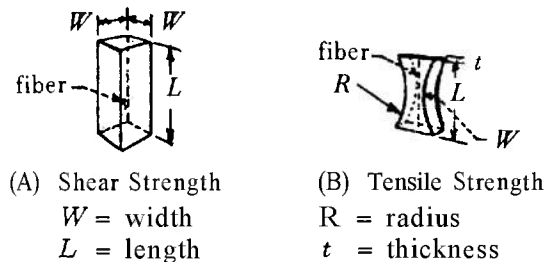
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Figure 2-5. Typical Load-Displacement Curve for Button-Type Test (Broutman, 1970)²

indirect test method for assessing the quality of interfacial bond. The dynamic modulus as well as the logarithmic decrement have also been used to obtain a measure of interfacial bond condition. Also the cleavage beam specimen has been used to investigate the interface contribution to fracture toughness?

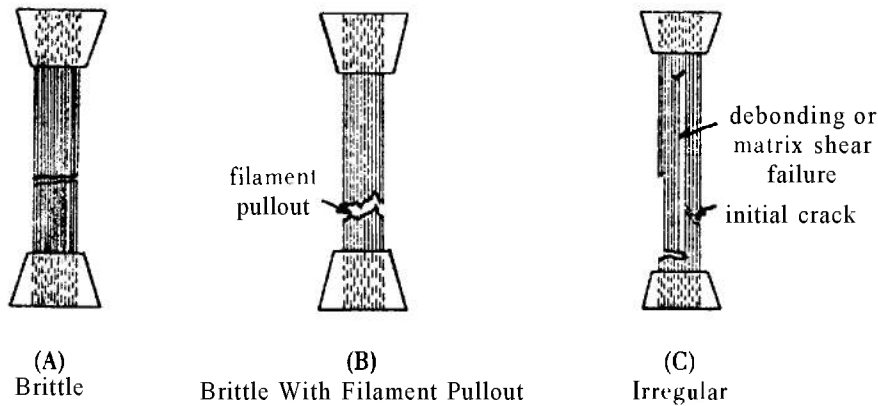
2-4.3 FRACTURE MORPHOLOGY AND INTERFACIAL BOND STRENGTH

The type of fracture can be a good indicator of the interfacial bond. A strong, intermediate, or weak bond produces a distinctly different fracture surface. Typical fracture surfaces of unidirectional composites loaded in tension along the fiber direction are illustrated in Fig. 2-7.



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Figure 2-6. Single-Fiber Specimens for Interface (For specimen dimension see Broutman, 1970)²



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Figure 2-7. Longitudinal Tensile Failure Modes (Chamis)²

The fracture surface of a specimen with a strong bond is fairly smooth across the cross section as shown in Fig. 2-7(A). Composites exhibiting this type of fracture surface are known to have high static strength and tend to be notch sensitive. The fracture surface of a specimen with intermediate bond strength is irregular and has some fiber pullout (see Fig. 2-7(B)). Fig. 2-7(C) shows the fractured surface of the composite with a very poor interfacial bond. This type of specimen has pronounced irregularity and fiber pullout.²

2-4.4 METHODS FOR PREDICTING STRESS AT THE INTERFACE

Several methods have been proposed for predicting the stress state at the interface, which can then be used to estimate the bond strength. The shear lag method has received extensive treatment by several investigators. This method determines the interface shear stress concentration at the end of the fiber as well as shear stress variation along the fiber. Additional methods include the Lamé solution for a shrink fit, classical elasticity boundary value problems, and finite-element analysis.

Fig. 2-8 presents a schematic of the model on which various analytical methods are based. A longitudinal section of the composite having a hexagonal fiber array is shown, and all the pertinent elements are identified.

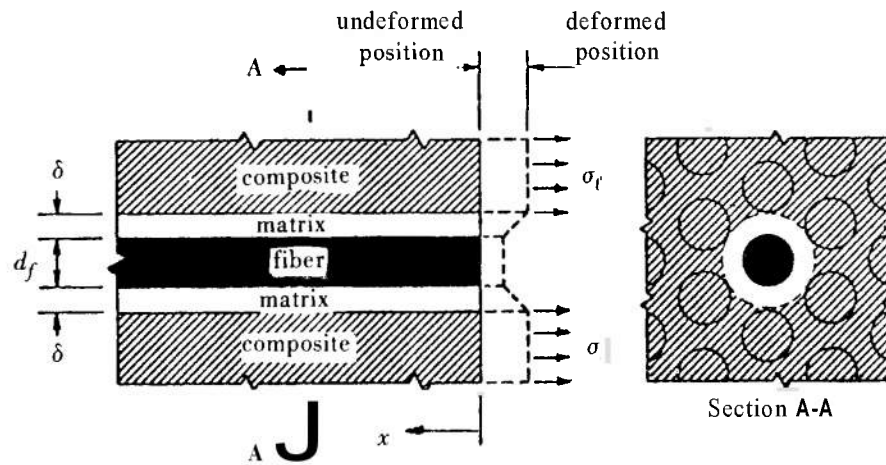
Some generalities derived from these investigations are:

1. The maximum stress concentration is at the end of the fiber and depends on the boundary conditions selected.
2. The maximum shear stress concentration depends on the fiber type and fiber volume ratio.
3. The maximum shear concentration at the end of the fiber remains almost constant at intermediate fiber volume ratios.
4. Shear concentration increases rather rapidly at low and high fiber volume ratios.
5. An ellipsoidal end yields the lowest interfacial shear stress concentration.
6. The interfacial shear stress decays within 2-3 fiber diameters from the fiber end when the end is bonded to the matrix.
7. Compressive radial stresses build up at the fiber end with a magnitude about that of the applied stress.

2-4.5 MICRORESIDUAL STRESS EFFECTS ON INTERFACIAL BOND STRENGTHS

The composite fabrication process inherently produces microresidual stresses at the interface. Both experimental and analytical methods have been advanced to investigate the microresidual stress state at the interface and to obtain an estimate of its effects on available interfacial bond strength.

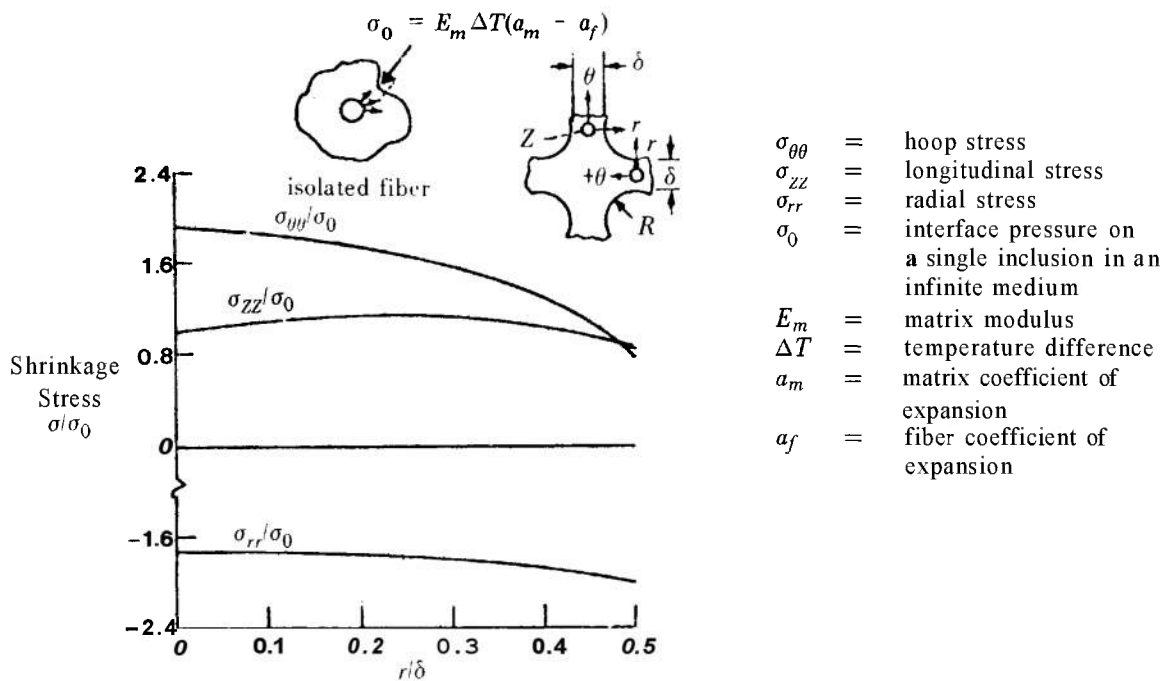
A photoelastic multifiber inclusion model is



d_f = fiber diameters
 δ = interface spacing
 σ_c = stress of unidirectional composite

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Figure 2-8. Schematic of Mechanism of Longitudinal Load Transfer in Fiber Composites (Chamis, 1972)²



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Figure 2-9. Distribution of Shrinkage Stresses Across Section Between Fibers (Fiber Volume Ratio = 0.5; $\delta/R = 0.5$ (Marloff and Daniel, 1968))²

shown in Fig. 2-9. The fiber arrangement for this investigation is the square array.

Classical elasticity analytical results for microresidual stresses have been based on the models in Figs. 2-8 and 2-10.

Generally, the analytical results of microresidual stresses are:

"1. The radial stress at the interface can be either tensile or compressive; its value depends on the stiffness of the constituents and increases as the E_f/E_m ratio decreases. It also depends on the fiber volume ratio and increases as this ratio increases.

"2. Shear stress exists along the fiber circumference and tends to locally debond the fiber within the matrix.

"3. The hoop stress at the interface in the matrix or interfacial bond is tensile and of relatively high magnitude".

The experimental results in Fig. 2-8 indicate that the microresidual radial stress is maximum midway between the fibers, whereas the analytical results indicate that it is maximum at the interface. However, both analytical and experimental results agree that the hoop and axial residual stresses in the matrix are tensile².

2-4.6 EFFECTS OF VOIDS AND ENVIRONMENT ON INTERFACIAL BOND STRENGTH

Experimental investigations have shown that voids, high temperature, and moisture affect interfacial bond strength and are detrimental to composite integrity and strength. As would be expected, the degrading effects of moisture are increased with increasing temperature².

2-5 GLASS FIBER REINFORCEMENT THEORY

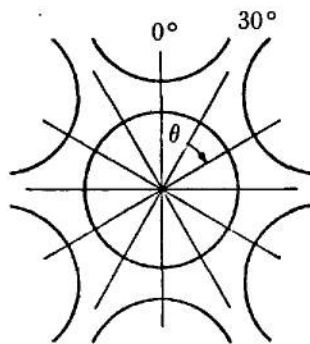
Much work has been done to provide a model for predicting composite behavior. A brief summary of the reinforcement theory is given in the paragraphs that follow. For more details the interested reader is referred to Refs. 2, 10, 13, 14, 17, 26, and the open literature.

2-5.1 CONTINUOUS FIBER REINFORCEMENT

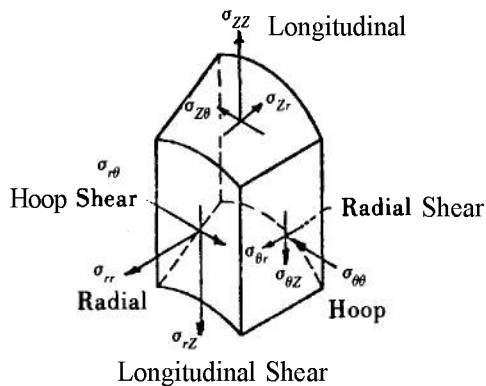
The composite behavior of a matrix reinforced with continuous, aligned fibrous reinforcement

σ_{rr} = radial stress
 σ_{zz} = longitudinal stress
 $\sigma_{\theta\theta}$ = hoop stress

σ_{rz} = longitudinal shear stress
 $\sigma_{r\theta}$ = hoop shear stress
 $\sigma_{\theta r}$ = radial shear stress



(A) Twelfefold Symmetry Lines in Hexagonal Array



(B) Stresses on Matrix Elements Adjacent to Fiber Matrix Interface

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Figure 2-10. General Arrangement of a Multifiber Composite (Chamis, 1972)²

has been studied well. By assuming that good dispersion, uniform distribution, and good inter-phase adhesion apply, the load applied to a composite is shared between the matrix and fiber phases. If both the fibers and matrix deform elastically, mechanical properties of the composite can then be predicted by the simple rule of mixtures as shown in Eqs. 2-1 and 2-2

$$E_c = E_f V_f + E_m V_m \quad (2-1)$$

$$\sigma_{uc} = \sigma_{uf} + \sigma'_m V_m \quad (2-2)$$

where

$$\sigma'_m = E_m \sigma_{uc} \quad (2-3)$$

E_c = modulus of composite

E_f = modulus of fiber

E_m = modulus of matrix

V_m = volume of matrix

σ'_m = stress in matrix at fiber failure strain

σ_{uc} = ultimate strength of composite

σ_{uf} = ultimate strength of fiber.

Eqs. 2-1 and 2-2 may be written in the form of Eqs. 2-4 and 2-5

$$E_c = E_f V_f + E_m (1 - V_f) \quad (2-4)$$

$$\sigma_{uc} = \sigma_{uf} + E_m \sigma_{uc} (1 - V_f) \quad (2-5)$$

When the fibers are misaligned or where the direction of testing is not coincident with the fiber axis, then the fiber contribution in Eqs. 2-4 and 2-5 must be reduced. When fibers are randomly dispersed in a plane, the term is reduced to a third; and if the fibers are randomly dispersed in three dimensions, the factor is one sixth. Thus a modified form of Eqs. 2-4 and 2-5, which contain an orientation factor K whose value may lie between 1 and 0.167, can be used¹³.

$$E_c = KE_f V_f + E_m (1 - V_f) \quad (2-6)$$

$$\sigma_{uc} = K\sigma_{uf} V_f + E_m \sigma_{uc} (1 - V_f) \quad (2-7)$$

2-5.2 DISCONTINUOUS FIBER REINFORCEMENT

When the fibers are discontinuous, the fiber can carry stress only by a shear transfer process at the interface. Kelly and Tyson¹⁷ have proposed a

model where there is a linear transfer of stress from the end of the fiber to a maximum value when the strain in the fiber is equal to that in the matrix. This has been shown to be a good approximation for polymer matrixes. Eq. 2-8 relates the maximum stress in the fiber to the fiber radius and the shear strength of the fiber matrix interface.

$$\frac{L}{\sigma_f} = \frac{r}{\tau} \quad (2-8)$$

where

L = fiber length

σ_f = peak stress in a fiber

r = fiber radius

τ = shear strength of the fiber matrix bond.

This leads to the concept of a critical fiber length L_c , i.e., the length which is necessary for the maximum stress in the fiber to reach a fiber fracture stress σ_{uf} . This may be written in the form of Eq. 2-9

$$L_c = \frac{\sigma_{uf} r}{\tau} = \frac{E_f \epsilon_{uc} r}{\tau} \quad (2-9)$$

where

L_c = critical fiber length for fiber failure

ϵ_{uc} = ultimate strain of the composite

σ_{uf} = ultimate strength of fiber

E_f = modulus of fiber

r = fiber radius

τ = shear strength of fiber matrix bond.

When the fiber length is less than the critical length, then the average stress $\bar{\sigma}_f$ in the fiber at composite failure is given by Eq. 2-10 and this is half the maximum stress in the fiber

$$\bar{\sigma}_f = \frac{L\tau}{2r} \quad (2-10)$$

where

$\bar{\sigma}_f$ = average stress in a fiber

L = fiber length

τ = shear strength of the fiber matrix bond

r = fiber radius.

If the fiber length is greater than the critical

length, then the average stress $\bar{\sigma}_f$ in the fiber is given by Eq. 2-11

$$\bar{\sigma}_f = E_f \epsilon_c \left(1 - \frac{E_f \epsilon_c r}{2L\tau} \right) \quad (2-11)$$

where

ϵ_c is the strain in the composite.

“The basis of the succeeding argument is that at any value of composite strain (ϵ_c) there is a critical fiber length, L_c and fibers shorter than this will carry an average stress as given in Eq. 2-10 which will always be less than $E_f \epsilon_c / 2$. Fibers longer than this carry an average stress as indicated in Eq. 2-11 which will always be greater than $E_f \epsilon_c / 2$; L_c will be given by Eq. 2-12”^{*13}.

$$L_c = \frac{E_f \epsilon_c r}{\tau} \quad (2-12)$$

where

L_c = critical fiber length at a composite strain ϵ_c

ϵ_c = strain in composite

E_f = modulus of fiber

τ = shear strength of the fiber matrix bond

r = fiber radius.

When the fibers are misaligned, then a correction factor of similar form to that given in Eqs. 2-6 and 2-7 must be used.

Discontinuous GRTP's contain a spectrum of fibers of different lengths. At low strains all fibers will make a contribution to the reinforcement as given by Eq. 2-11 since L_c will be small. As the strain is increased, a progressively smaller proportion of the fibers will reinforce according to Eq. 2-11 and an increasing proportion will follow Eq. 2-10. Therefore, the slope of the load extension curve for such a material can be expected to decrease as the extension (strain) is increased. A mathematical model of this behavior was constructed by Bowyer and Bader combining the concepts of Eqs. 2-7, 2-10, 2-11, and 2-12.

This equation is shown as Eq. 2-13

$$\sigma_c = CX + CY + Z. \quad (2-13)$$

“The first term (on the right-hand side of Eq. 2-13) is the contribution of the subcritical fibers, the second term that of the supercritical fibers, and the third term that of the matrix. The individual terms are expanded in Eqs. 2-14, 2-15, and 2-16”^{*13}.

$$X = \sum^{L_i < L_c} \frac{\tau L_i V_i}{2r} \quad (2-14)$$

$$Y = \sum^{L_j > L_c} E_f \epsilon_c \left(1 - \frac{E_f \epsilon_c r}{2L_j \tau} \right) V_j \quad (2-15)$$

$$Z = E_m \epsilon_c (1 - V_f) \quad (2-16)$$

where

L_i = subcritical fiber subfraction

V_i = subcritical volume subfraction

L_j = supercritical fiber subfraction

V_j = supercritical volume subfraction.

These three terms are then combined in Eq. 2-17

$$\sigma_c = C \left[\sum^{L_i < L_c} \frac{\tau L_i V_i}{2r} + \sum^{L_j > L_c} E_f \epsilon_c \left(1 - \frac{E_f \epsilon_c r}{2L_j \tau} \right) V_j \right] + E_m \epsilon_c (1 - V_f). \quad (2-17)$$

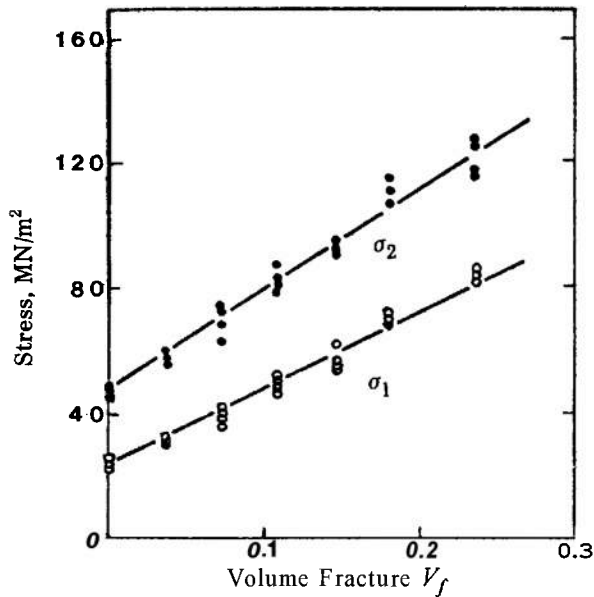
“In practical systems the terms E_f , ϵ_c and r can be readily obtained, and the relationships between σ_c and ϵ_c may be obtained from a tensile test”^{*13}. The orientation factor C and τ are generally not known, but the fiber length distribution can be determined.

If the assumption is made that the orientation factor C is independent of strain and is the same for all fiber lengths at least at small strains, then this model allows both C and τ to be determined from tensile test data.

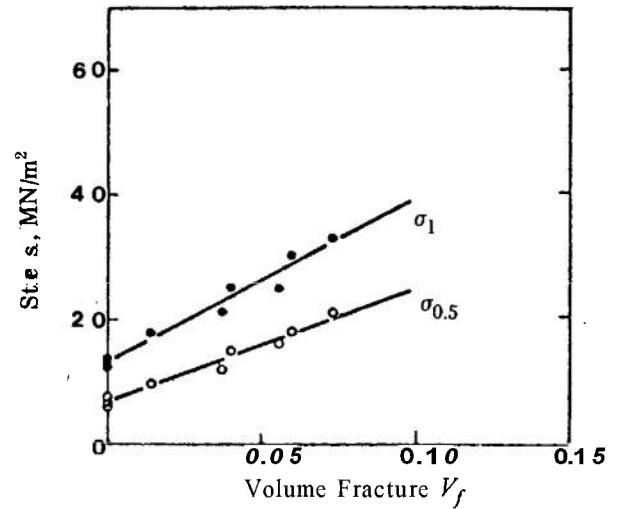
2-5.3 EFFECT OF COMPOSITE VARIABLES ON PERFORMANCE

Considerable investigative work has been done to elucidate the various aspects of the glass reinforcement theory in an attempt to predict and improve composite performance. Refs. 2, 10, 13, 14,

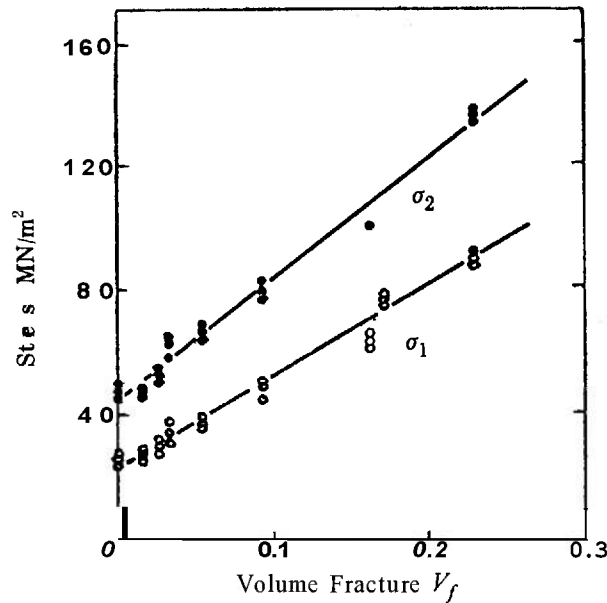
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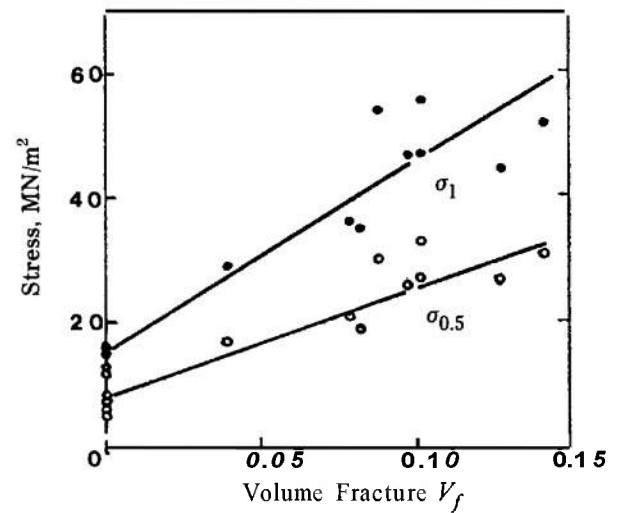
(A) Stress at Strains of 0.01 and 0.02 vs V_f for Glass/Nylon, A Material



(C) Stress at Strains of 0.005 and 0.01 for Glass Polypropylene, C Material



(B) Stress at Strains of 0.01 and 0.02 vs V_f for Glass/Nylon, B Material



(D) Stress at Strains of 0.005 and 0.01 for Glass Polypropylene, D Material

Material	Resin	Glass Fiber
A	Nylon 6/6 ICI Maranyl A-100	E glass 12 μ m diam. origin unknown
B	Nylon 6/6 ICI Maranyl A-100	E glass 12 μ m diam. size PVA/methacrylo- chromic chloride

Material	Resin	Glass Fiber
C	Polypropylene copolymer ICI-8639	E glass 12 μ m diam. Fibreglass Ltd Size ref. MSS-1607
D	Polypropylene homopolymer ICI-543	E glass 12 μ m diam. Fibreglass Ltd Size ref. MSS-1607

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Figure 2-11. Stress vs Volume of Glass Fiber for Nylon and Polypropylene¹³

15, 16, 18, 19, 20, and 21 report on some of the recent work. In any attempt to improve the performance of discontinuous glass fiber reinforced composites the variables at one's disposal are volume of fiber, fiber length and diameter, fiber orientation, and shear strength of the fiber matrix bond. Some examples of the studies and their results are given in the paragraphs that follow for several composite systems.

2-5.3.1 Volume of Glass Fiber

Fig. 2-11 and Table 2-15 as well as the property data in Chapter 3 indicate that increased fiber volume leads to increased strength and modulus and to decreased elongation to fracture. Tough-

ness, which depends upon both strength and elongation, does not show a general trend-with increasing fiber concentration.

Although the actual stiffness may be increased by increasing the fiber concentration, there is a disadvantage in that the melt flow properties of the composite deteriorate. Therefore, it becomes more difficult to mold the material.

According to Ongchin, Olender, and Ancker¹⁰, there exists a critical volume fraction of fibers V_{fc} below which any fiber longer than L_f will break prior to fracture of the composite specimen itself:

$$V_{fc} = \frac{\sigma_m^u - (\sigma_m)_\epsilon u_f}{\sigma_f^u + \sigma_m^u - (\sigma_m)_\epsilon u_f} \quad (2-18)$$

TABLE 2-15. TENSILE PROPERTIES OF UNIDIRECTIONAL COMPOSITE MATERIALS TESTED PARALLEL TO FIBER AXIS^{1,6}

Matrix	Reinforcement	Fiber Percent by Vol.	Specific Gravity	Tensile Strength, psi	Tensile Modulus, psi	Ultimate Elongation, %	Curve Area in. • lb/in. ³
lonomer	None	—	0.95	1,810 (yield)	23,500	17 (yield)	229 (yield)
	Glass ^a	10	1.11	8,390	543,000	2.25	105
		20	1.27	12,300	920,000	2.0	138
		30	1.42	14,100	1,274,000	1.35	105
		40	1.58	16,000	1,620,000	1.17	87
Polyethylene, HD	None	—	0.95	3,250 (yield)	155,000	13 (yield)	301 (yield)
	Glass ^a	10	1.11	10,500	649,000	2.13	52
		20	1.27	20,700	1,370,000	1.91	212
		30	1.42	22,600	1,570,000	1.92	295
		40	1.58	23,800	2,052,000	1.30	158
		50	1.74	20,700	2,216,000	1.21	141
Polycarbonate	None	—	1.20	8,920 (yield)	280,000	6.2 (yield)	339 (yield)
	Glass ^a	10	1.33	12,850	785,000	1.98	167
		20	1.47	16,540	1,093,000	1.79	178
		30	1.60	23,170	1,707,000	1.56	185
		40	1.73	26,230	2,098,000	1.40	145
Polymethylmethacrylate	None	—	1.19	10,600	381,000	4.6	301
	Glass ¹	10	1.32	13,050	958,000	1.64	189
		20	1.46	17,700	1,520,000	1.28	180
		30	1.59	17,560	2,180,000	1.0	110
		40	1.73	24,800	2,010,000	1.8	120

¹Owens Corning Type 801 E glass

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where

- σ_m^u = ultimate tensile strength of the matrix
- σ_f^u = ultimate tensile strength of the fibers
- $(\sigma_m)\epsilon_f$ = matrix stress at the failure strain of the fiber.

Depending on the value used for the tensile strength of the glass fibers, the critical fiber concentration for glass reinforced polyethylene was reported to be at least one-half the weight percentage. Accordingly, when broken in tension, specimens containing a glass concentration lower than V_{fc} will show internal fracture of the fibers with the maximum length being the critical fiber length”.

2-5.3.2 Glass Strand Solids

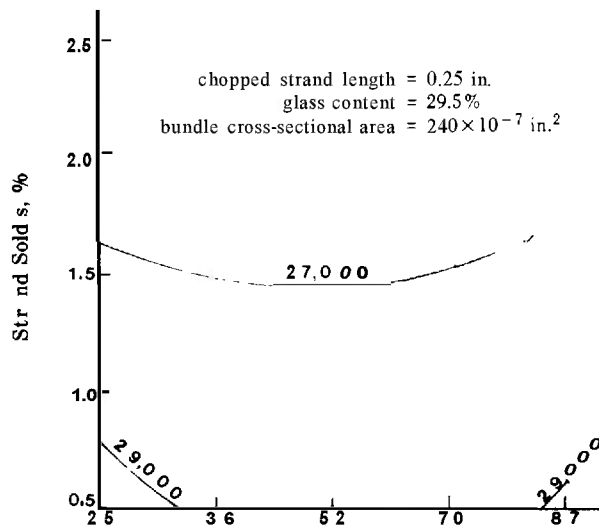
The strand solids have a significant effect on properties. For example, their effect on flexural strength on nylon 6/6 is shown in Fig. 2-12. Strand solids are defined as the amount of coating on the fiberglass surface. It is given as the percent by weight of the fiberglass strand. The flexural

strength of nylon increases with a decrease in strand solids. At lower strand solids, the decrease in flexural strength with an increase in filament diameter is more dramatic.

The glass content versus strand solids in Fig. 2-13 is shown to be another significant variable. This figure shows the quadratic effects of strand solids and the linear effects of glass content on the flexural strength of nylon 6/6 using medium diameter filaments.

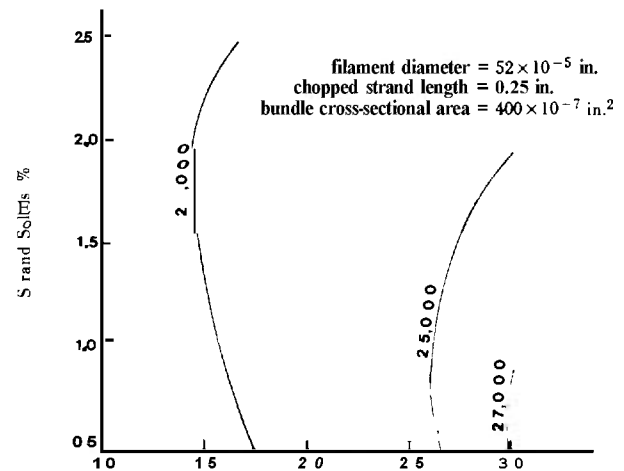
The increase in amount of glass introduces larger quantities of organic sizing materials. This larger quantity of sizing materials begins to either plasticize the matrix resin or cause a poor interface bonding. Fig. 2-13 shows this effect and the necessity for adjusting strand solids. Flexural strength lines seem to be moving toward an optimum glass content-strand solids point shown in Fig. 2-14.

The glass content and strand solids interaction for polypropylene is shown in Fig. 2-15. The optimum fiberglass strands for polypropylene are related to the bundle size and strand solids. Therefore, at low glass loadings the amount of strand solids should be increased to maintain the same properties as with the optimum glass loading. With higher glass loadings, or larger surface



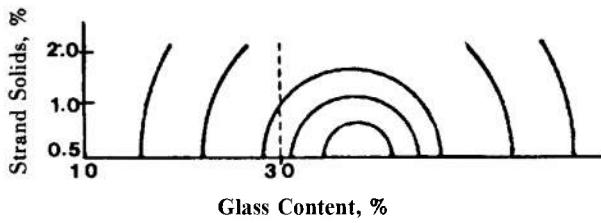
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Figure 2-12. Flexural Strength—Filament Diameter vs Strand Solids, Nylon 6/6 (Ref. 21)



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Figure 2-13. Flexural Strength—Glass Content vs Strand Solids²¹



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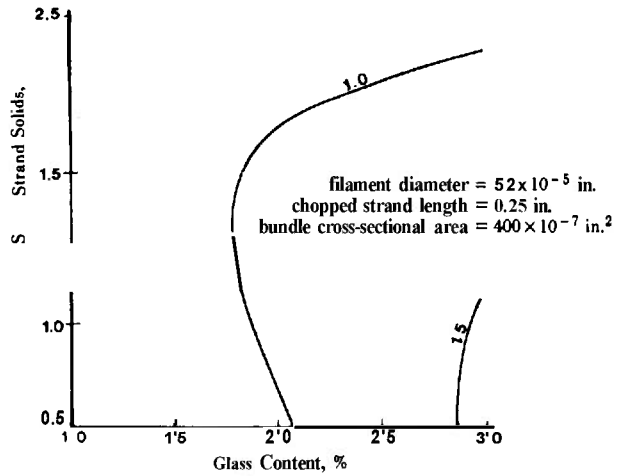
Figure 2-14. Strand Solids—Glass Content Plot—Production of Optimum Conditions²¹

area, an increase in strand solids is necessary to maintain flexural strength. A similar strand solids/glass content interaction applies for flexural modulus (see Fig. 2-28).

The Izod impact strength of nylon 6/6 is affected by the linear effect of glass content and the quadratic effect of bundle size strand solids.

Fig. 2-16 shows that using a constant bundle size of $400 \times 10^{-7} \text{ in.}^2$ and increasing glass content while reducing strand solids improves the impact strength of nylon 6/6.

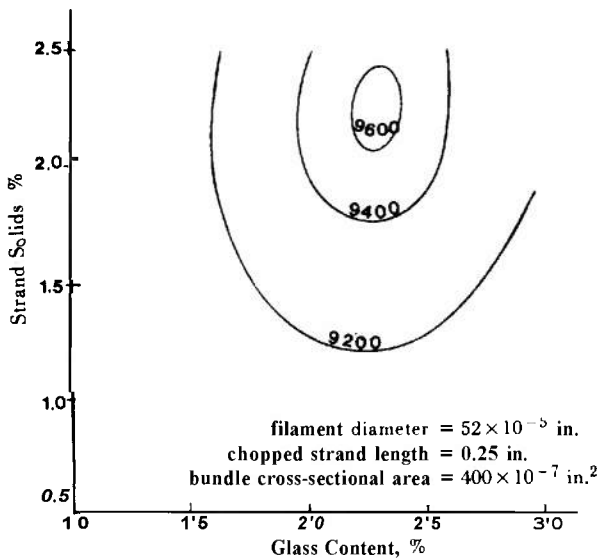
Figs. 2-17 and 2-18 show that impact properties of polypropylene increase with an increase in glass content and that a lower amount of sizing is required for this property.



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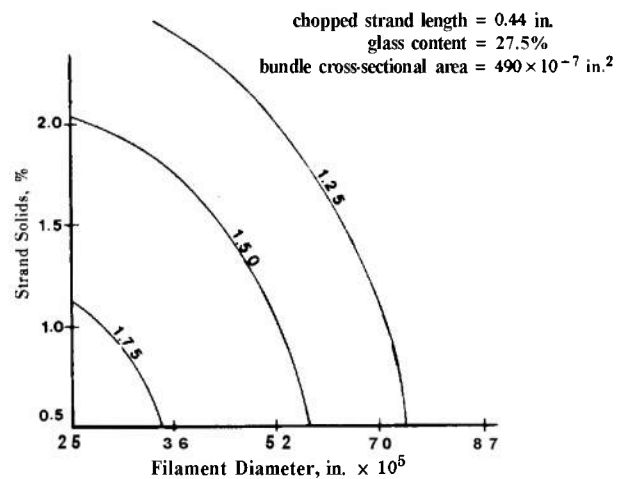
Figure 2-16. Izod Impact—Glass Content vs Strand Solids, Nylon 6/6 (Ref. 21)

Fig. 2-19 indicates how the heat deflection temperature of the nylon composite can be affected by the sizing on the fiberglass. For example, the higher the amount of sizing on the fibers, the less the penetration or insufficient surface wetting causes a lowering of heat deflection temperature. Increasing the amount of glass in the composite can, however, increase surface



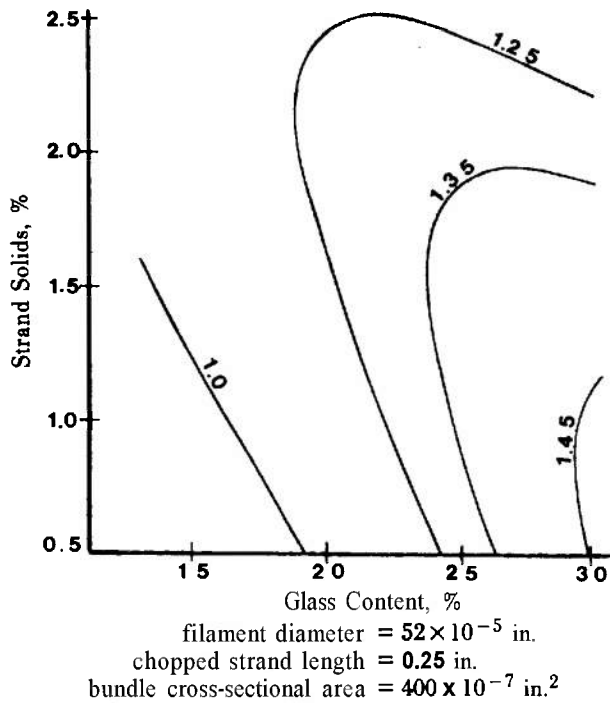
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Figure 2-15. Flexural Strength—Glass Content vs Strand Solids, Polypropylene²¹



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Figure 2-17. Izod Impact—Filament Diameter vs Strand Solids, Polypropylene²¹



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Figure 2-18. IZOD Impact—Glass Content vs Strand Solids, Polypropylene²¹

area and increase the heat deflection temperature significantly as shown in Fig. 2-36. This increase provides larger contact surface area. Fig. 2-20 shows that the heat deflection temperature is increased by increasing surface area.

Also, the higher quantity of sizing on the glass surface can introduce a larger amount of low melting materials—i.e., lubricants, plasticizers, etc. At high temperatures, these materials soften and cause failure at the interface thus lowering the heat deflection temperature²¹.

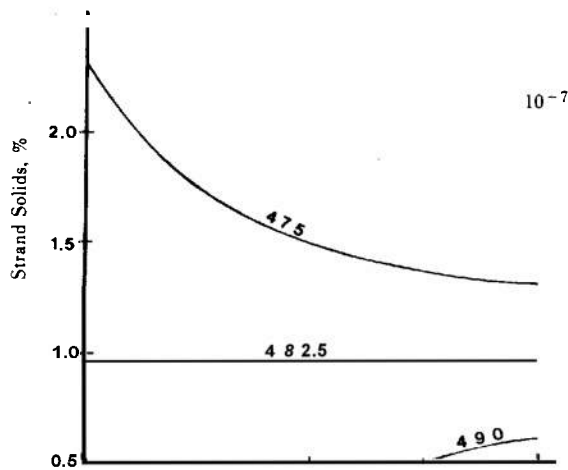
The same mechanism, i.e., effect of surface area of filaments, also applies for polypropylene (see Fig. 2-21).

2-5.3.3 Glass Strand Bundle Size

Strand bundle size is defined as the number of filaments of a specified filament diameter. The strand is assumed to be a cylinder, and it is identified by its cross-sectional area in square inches.

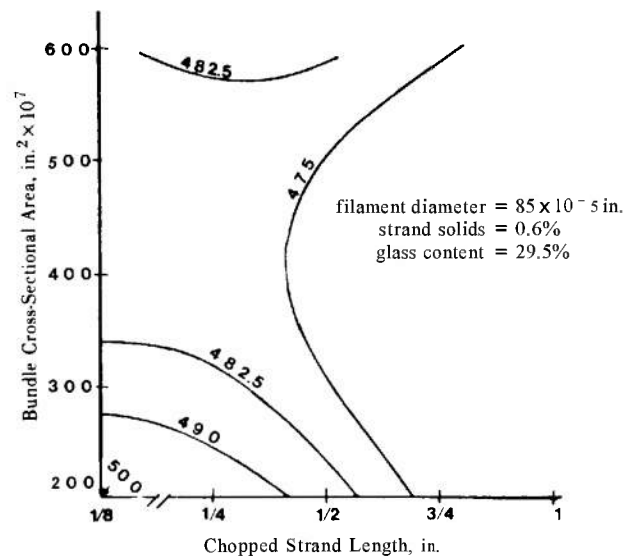
Fig. 2-22 indicates that the optimum flexural strength of nylon 6/6 is obtained using small bundle sizes.

The quadratic effect of bundle size on flexural strength is shown in Fig. 2-23 for polypropylene. There is a continuing increase in strength with



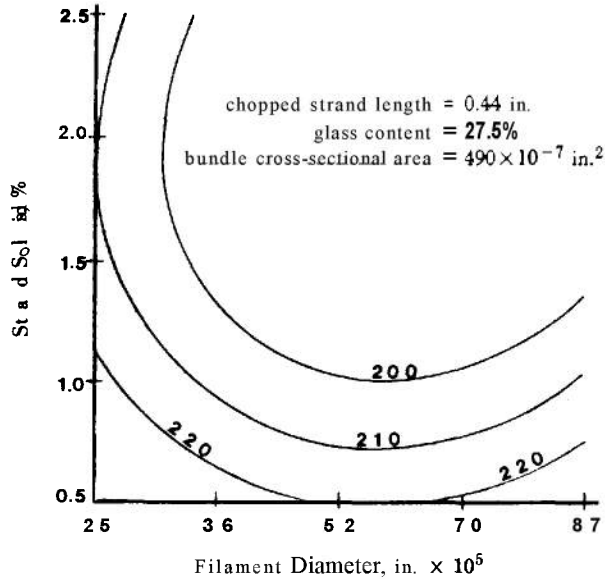
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Figure 2-19. Heat Deflection Temperature—Filament Diameter vs Strand Solids, Nylon 6/6 (Ref. 21)



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Figure 2-20. Heat Deflection Temperature—Chopped Strand Length vs Bundle Cross-Sectional Area, Nylon 6/6 (Ref. 21)



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Figure 2-21. Heat Deflection Temperature—
Filament Diameter vs Strand Solids,
Polypropylene²¹

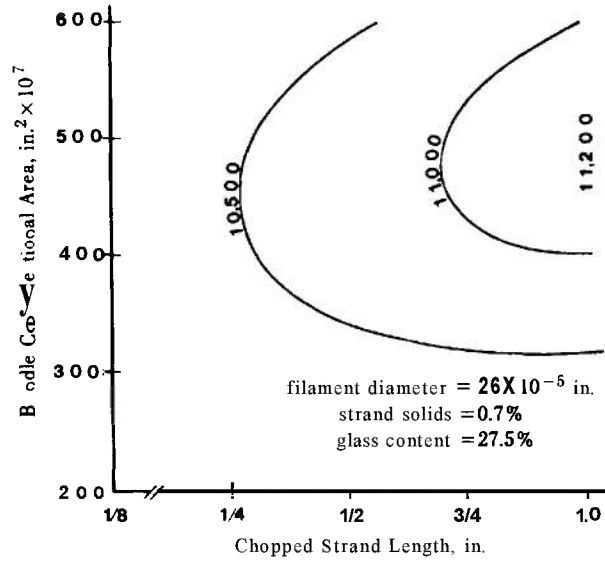
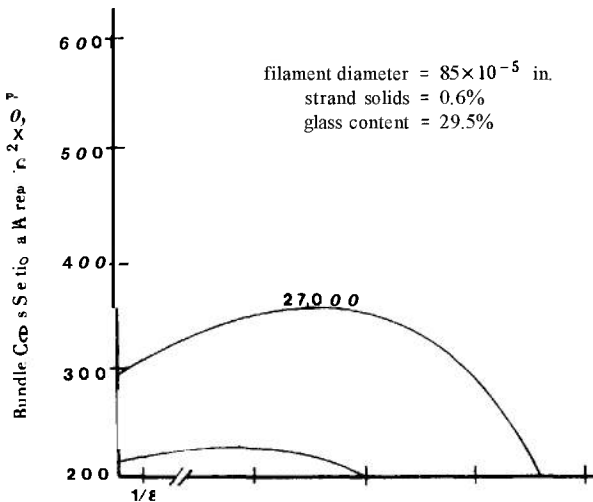


Figure 2-23. Flexural Strength—Chopped
Strand Length vs Bundle Cross-Sectional Area,
Propylene²¹



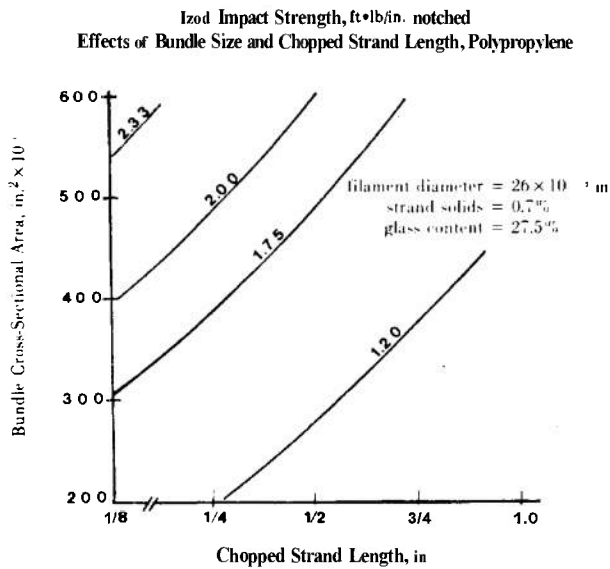
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Figure 2-22. Flexural Strength—Chopped
Strand Length vs Bundle Cross-Sectional Area,
Nylon 6/6 (Ref. 21)

the injection molding process. Therefore, there are various filament bundle sizes in the molded part. The distribution of different bundle sizes in the part depends on the size of the original bundles and the amount of protective coating on the strand (strand solids). There will be a greater number of large bundles with a larger amount of glass in the premix or with a greater amount of protective coating.

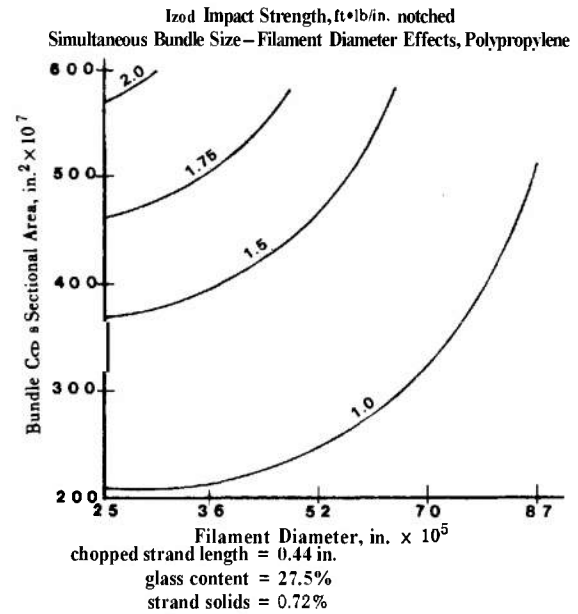
polypropylene.

The heat deflection temperature of polypropylene is affected primarily by surface area (see Fig. 2-26). Therefore, the relationship of bundle size/strand solids is similar to that described previously for strand solids.



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Figure 2-24. Izod Impact — Chopped Strand Length vs Bundle Cross-Sectional Area, Polypropylene²¹



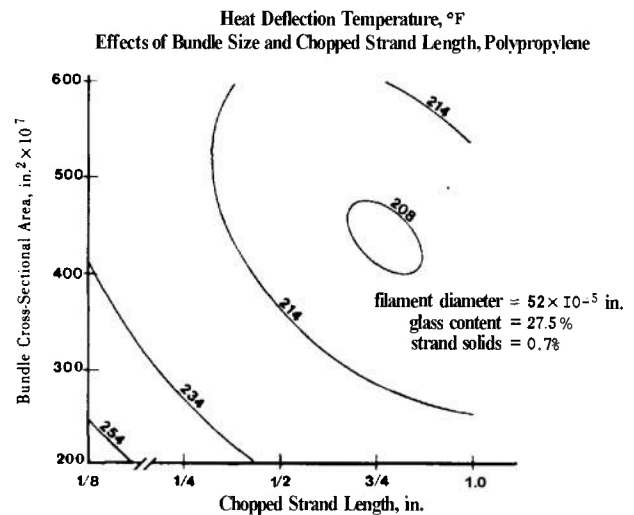
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Figure 2-25. Izod Impact — Filament Diameter vs Bundle Cross-Sectional Area, Polypropylene²¹

2-5.3.4 Glass Filament Diameter

In nylon, the flexural strength decreases with an increase in filament diameter to about 50×10^{-5} in. as shown in Fig. 2-12 and then increases with filament diameter. There are two points representing 29,000 psi flexural strength at a strand solid level of 0.7%. At the low filament diameter region, 30×10^{-5} in., and bundle size of 240×10^{-7} in², there are a larger number of filaments. Therefore, the glass surface area available to come in contact with the matrix is very large. Thus this region represents an effective use of the fiberglass surface. This efficiency is reduced with the increase in filament diameter. The strand solids should now be reduced to allow better penetration of matrix polymer into the bundles.

In the large filament diameter region, a different phenomenon prevails. Now there are large rods with high modulus contributing to the reinforcement. However, the surface area also continues to play an important role. As shown in Fig. 2-22 the optimum flexural strength is obtained using small bundle sizes. The flexural strength of nylon, therefore, seems to be significantly affected by the filament diameter-strand solids in-



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Figure 2-26. Heat Deflection Temperature — Chopped Strand Length vs Bundle Cross-Sectional Area, Polypropylene²¹

teraction. This interaction has a quadratic effect. The glass content is also significant and has linear effect (Fig. 2-35).

Filament diameter is a significant variable affecting the flexural strength of polypropylene. The glass content effect is significant but reaches an optimum level at 23% loading. In Fig. 2-27, the flexural strength increases with a decrease in filament diameter.

Table 2-18 indicates that a 10- μ m filament diameter is superior to a 13- μ m diameter for polystyrene tensile and flexural properties. This is attributed to the lower aspect ratio of the 13- μ m filament.

The effect of filament diameter on the flexural modulus of nylon 6/6 is given in Fig. 2-28. The significant variables for flexural modulus are filament diameter and glass content.

Although glass content is the most significant factor affecting the flexural modulus of polypropylene, there is an optimum fiber diameter for this property as shown in Fig. 2-29.

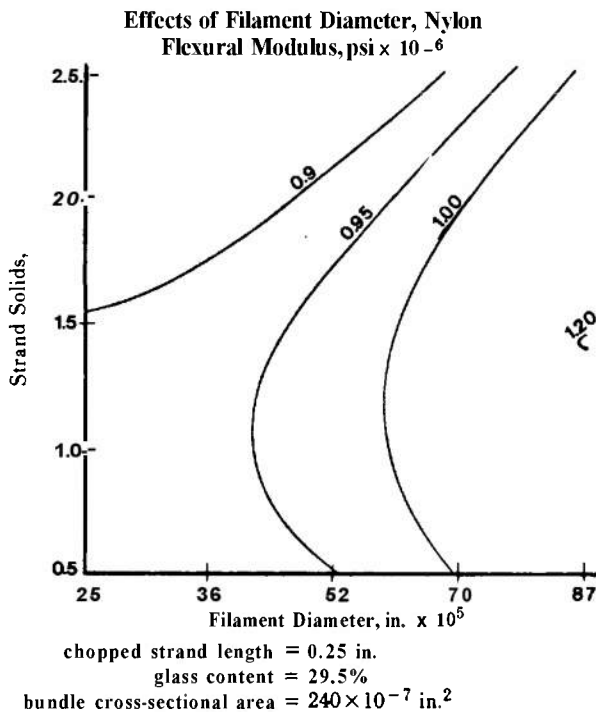
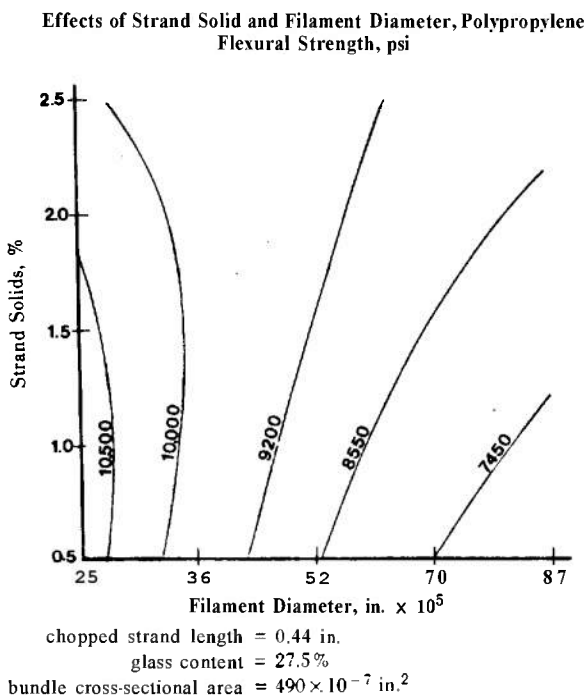
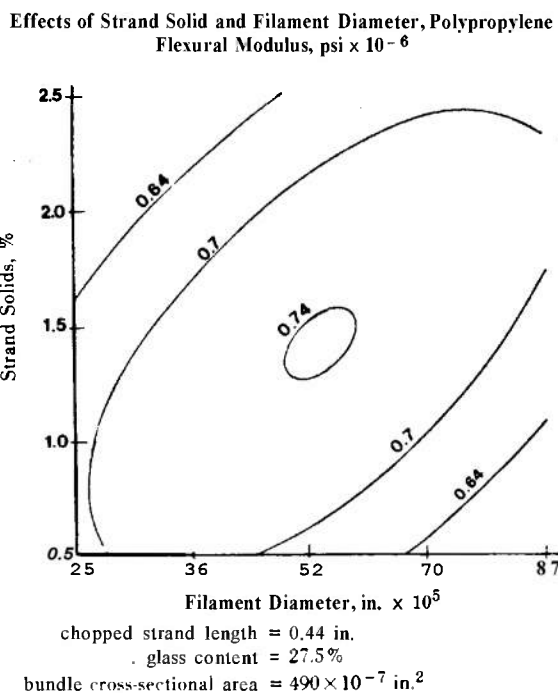


Figure 2-28. Flexural Modulus—Filament Diameter vs Strand Solids, Nylon²¹



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Figure 2-27. Flexural Strength—Filament Diameter vs Strand Solids, Polypropylene²¹



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Figure 2-29. Flexural Modulus—Filament Diameter vs Strand Solids, Polypropylene²¹

The filament diameter of nylon has a linear effect on Izod impact strength as shown in Fig. 2-30. Higher impact strengths are obtained using larger filament diameters.

In polypropylene, all variables affect impact strength significantly. Fig. 2-31 indicates that the smaller diameter filaments are superior.

Figs. 2-32 and 2-33 indicate that the same fiber-glass variables apply to the tensile strength as well as the impact properties.

Heat deflection temperatures for strand solids and filament diameter are given in Figs. 2-19 and 2-21 for both polymer systems.

2-5.3.5 Glass Fiber Length

The chopped strand length is more significant in polypropylene than in nylon. This is attributed to the lower viscosity of the polymer melt and the easier flow of fiberglass strands through it. The longer strands will tend to assume a straighter position than in nylon, where this orientation is resisted by the higher melt viscosity.

An increase in chopped strand length lowers the heat deflection of nylon (Fig. 2-36). Strands longer than 0.5 in. are distributed in the polymer matrix differently than the short strands. The long fibers tend to flow poorly and/or leave unreinforced spots in the polymer. The short strands distribute themselves better and cover larger areas in the polymer.

Additional data are shown in Figs. 2-19, -20, -21, -22, -23, -24, and -26 for flexural strength and heat-deflection temperatures of nylon 6/6, and Izod impact and heat deflection temperatures of polypropylene. See also par. 2-5.2 for discussion of critical fiber length.

2-5.3.6 Glass Fiber Orientation

Maximum stiffness properties are obtained when the glass fibers are fully aligned and tested in the direction of alignment. Significant reduction in the tensile strength and flexural modulus occurs as the fibers are randomly aligned. This is illustrated in Table 2-16, where a 20% glass fiber reinforced resin was molded using a 300-ton HPM reciproscrew injection machine and a ram type injection machine with a "torpedo" to separate the flow. The significant reduction in tensile strength and flexural modulus with the ram-molded specimens is attributed to the observed lack of alignment of the glass fibers. Varying the melt temperature over the range 425° to 525° F did not improve the properties²⁷.

If the fibers are randomly oriented in three dimensions, the reinforcing effect would be 0.167 of uniaxially aligned fibers measured in the fiber alignment direction and the composite would be isotropic. If the fibers are randomly oriented in a plane, the factor is 0.33. Some degree of fiber orientation is obtained during fabrication. If this

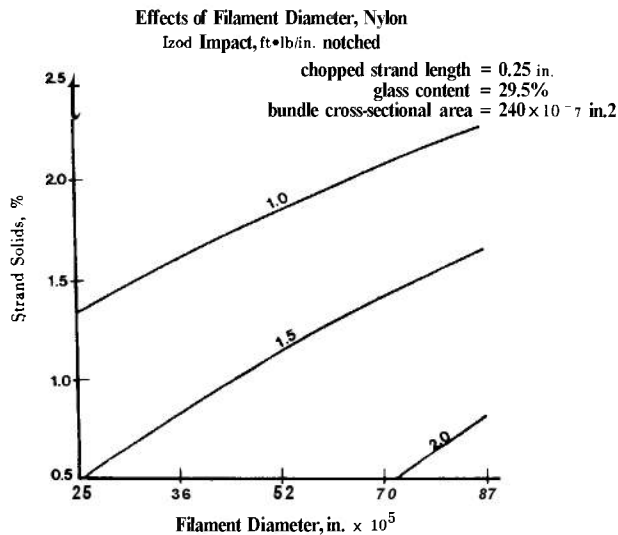


Figure 2-30. Izod Impact—Filament Diameter vs Strand Solids, Nylon 6/6 (Ref. 21)

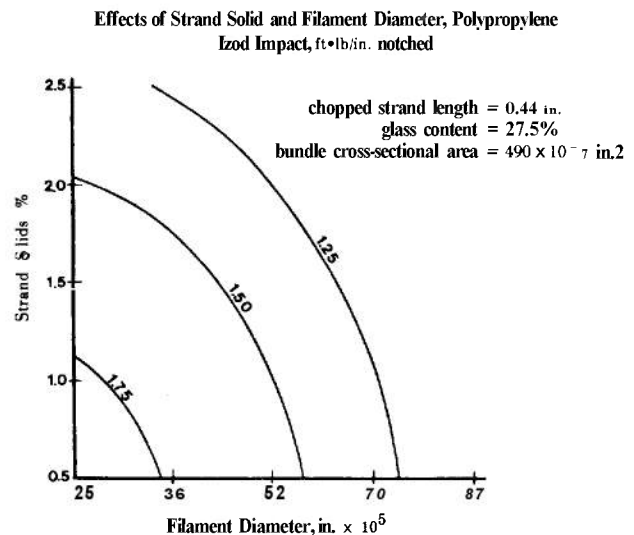
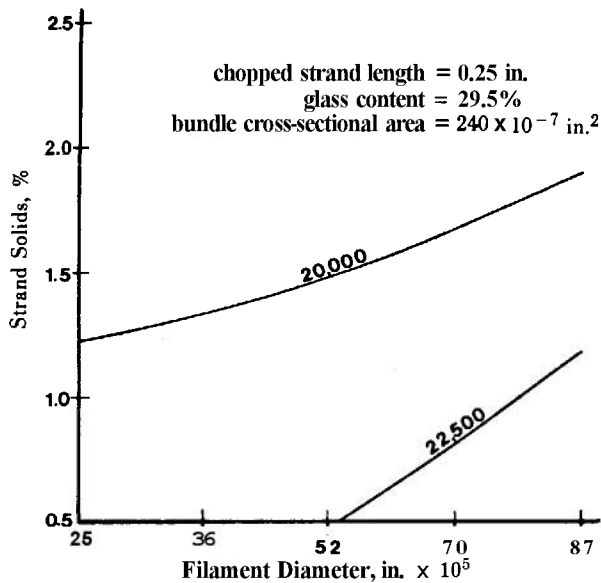


Figure 2-31. Izod Impact—Filament Diameter vs Strand Solids, Polypropylene²¹

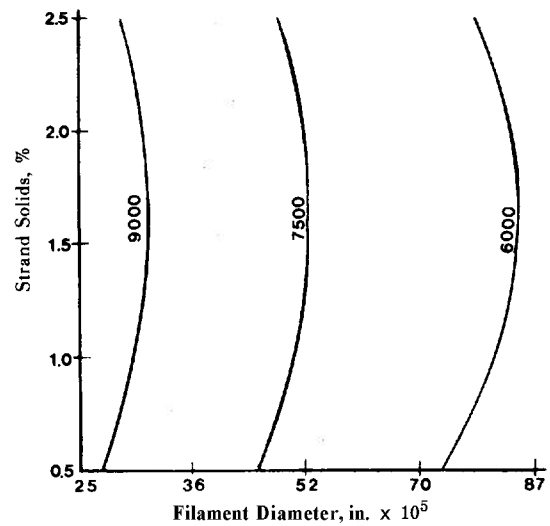
Effects of Filament Diameter, Nylon
Tensile Strength, psi



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Figure 2-32. Tensile Strength—Filament Diameter vs Strand Solids, Nylon 6/6 (Ref. 21)

Effects of Strand Solid and Filament Diameter, Polypropylene
Tensile Strength, psi



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Figure 2-33. Tensile Strength—Filament Diameter vs Strand Solids, Polypropylene²¹

TABLE 2-16. MOLDING CONDITIONS AFFECT THE MECHANICAL PROPERTIES OF PRECOMPOUNDED 20% GLASS FIBER REINFORCED PROPYLENE POLYMER²⁷

Resin Property	Molding Equipment Used			
	Reciproscrew	Ram		
Melt Temperature during Molding, °C	425	425	475	525
Tensile Strength at Break, psi	11,400	9,600	9,900	9,900
Flexural Modulus, psi				
Secant	550,000	450,000	450,000	480,000
Tangent	590,000	475,000	495,000	—
HDT at 264 psi, °C	142	141	142	142
Notched Izod Impact Energy at RT, ft•lb/in.	1.6	1.4	1.3	1.5

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can be made to coincide with the service stress direction, it can improve properties. However, this will be offset by somewhat reduced properties in the other directions²⁸.

A summary of the effects of geometric variables on the properties of nylon 6/6 and polypropylene composites is given in Table 2-17 and Figs. 2-34 through 2-37.

2-5.3.7 Thermoplastic Matrix Properties

The chemistry of the thermoplastic matrix affects the performance of the fiberglass. The

matrix variables that influence the reinforcement mechanism include the active functional group on the polymer chain and the molecular weight or the viscosity of the polymer at its processing temperatures.

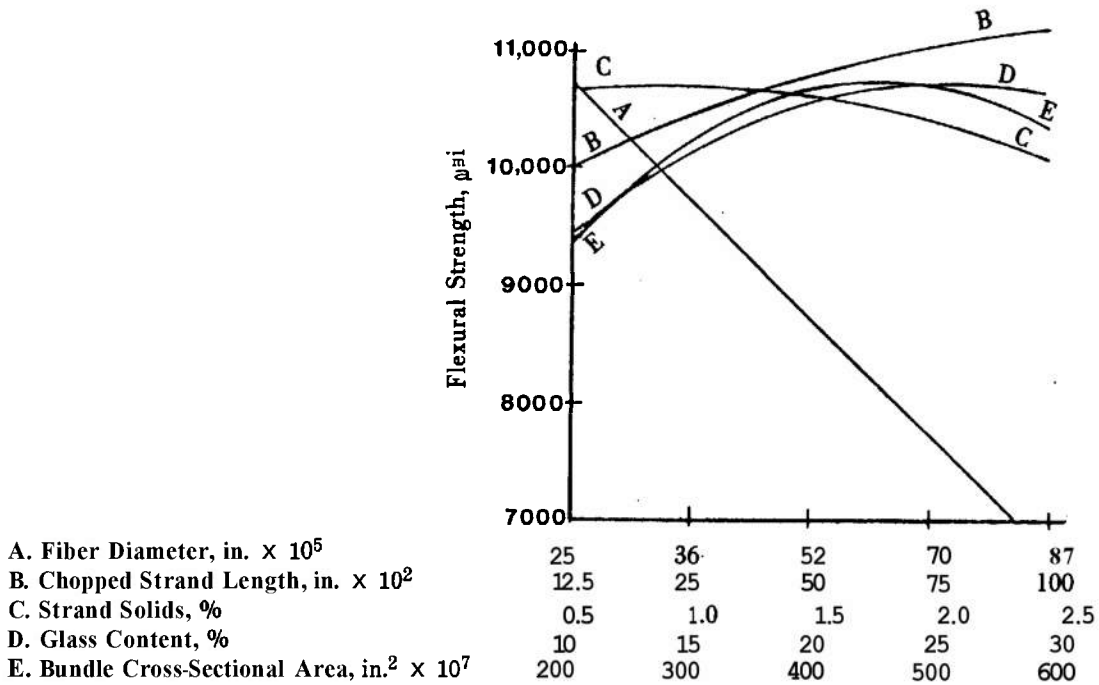
The polymer viscosity influences the mobility of the filaments in the melt and therefore their distribution in the molded parts. The higher viscosities act as shearing forces to degrade the glass bundles and influence the bundle size distribution in the matrix polymer system.

The chemical functionality of the plastics, i.e., their affinities for the glass surface, is illustrated

TABLE 2-17. THERMOPLASTIC REINFORCEMENT DESIGN VARIABLES EFFECT²¹

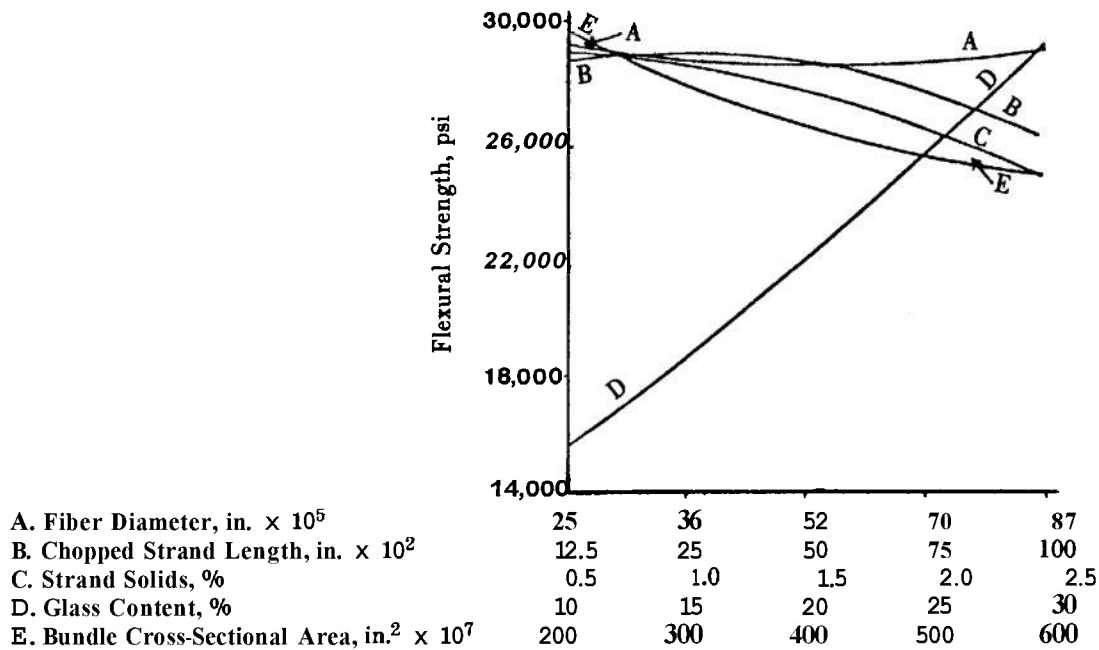
Resin	Response	Linear Effect	Quadratic Effect
Polypropylene	Flexural Strength	Filament Diameter Glass Content Chopped Strand Length	Bundle Size Interaction of Filament Diameter and Strand Solids
	Flexural Modulus	Chopped Strand Length Glass Content	---
	Izod Impact (notched)	Filament Diameter Glass Content Bundle Size	--
	Tensile Strength	Filament Diameter Glass Content	Filament Diameter Chopped Strand Length
	Heat-Deflection Temperature	Filament Diameter Glass Content	Interaction of Chopping Lengths and Glass Content Interaction of Strand Solid and Glass Content
Nylon	Flexural Strength	Filament Diameter Strand Solids Chopped Strand Length Glass Content	Filament Diameter – Strand Solid Interaction
	Flexural Modulus	Filament Diameter Glass Content	--
	Izod Impact (notched)	Glass Content	Interaction of Strand Solids and Bundle Size
	Tensile Strength	Filament Diameter Glass Content	--
	Heat Deflection Temperature	Filament Diameter Glass Content	--

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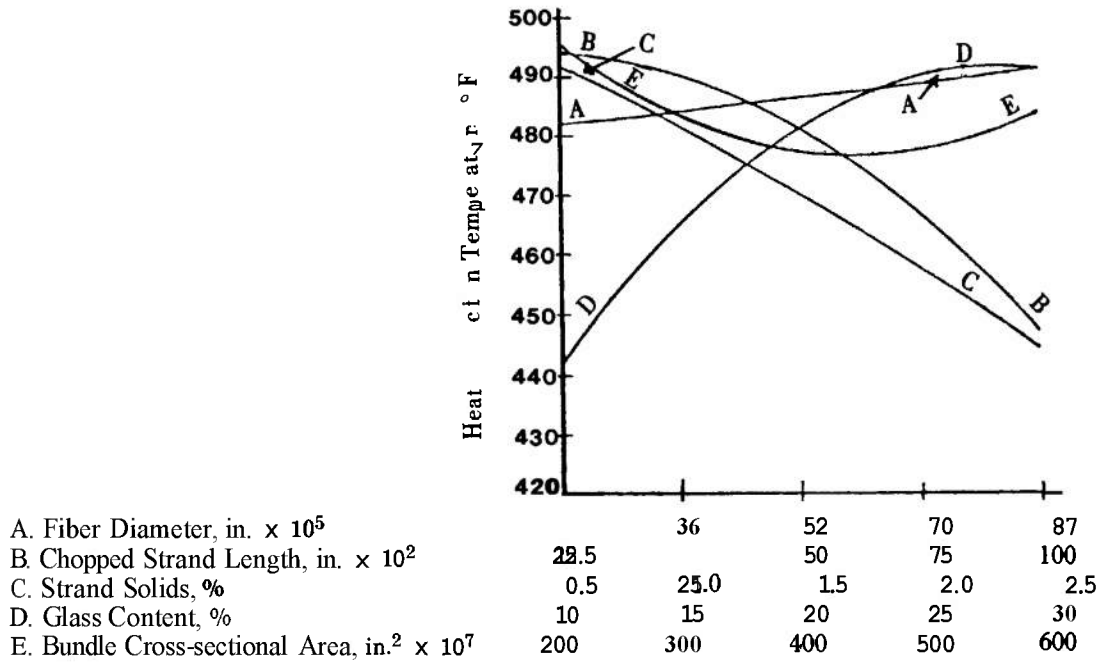
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Figure 2-34. Flexural Strength—Interdependence With Fiberglass Variables, Polypropylene²¹



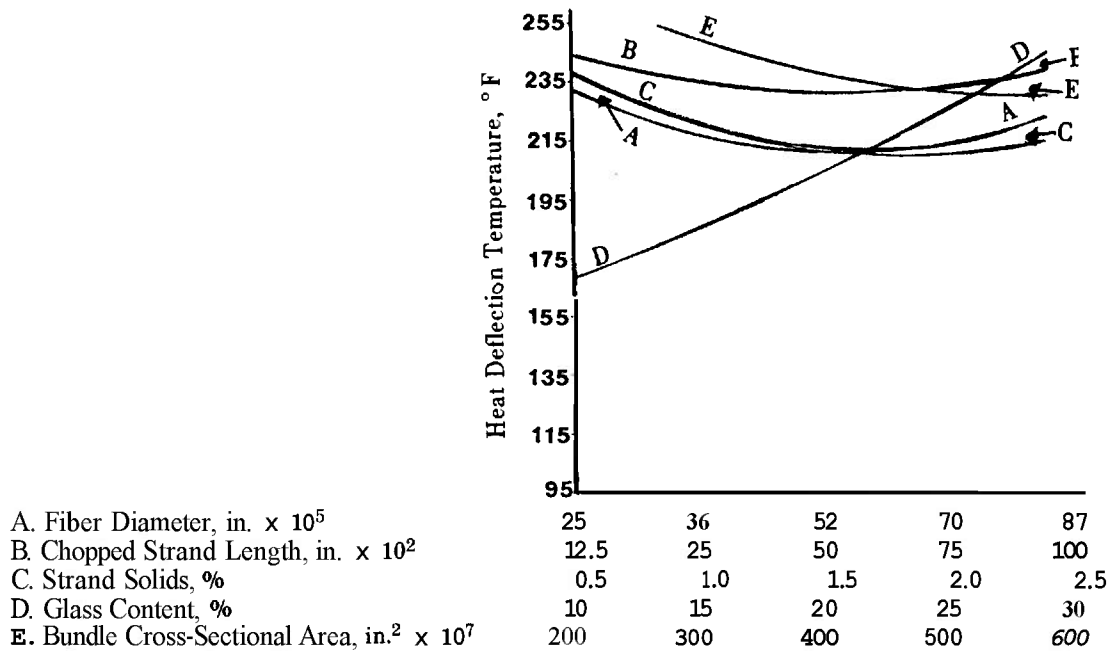
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Figure 2-35. Flexural Strength—Interdependence With Fiberglass Variables, Nylon 6/6 (Ref.21)



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Figure 2-36. Heat Deflection Temperature—Interdependence With Fiberglass Variables, Nylon 6/6 (Ref. 21)



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Figure 2-37. Heat Deflection Temperature—Interdependence With Fiberglass Variables, Polypropylene²¹

by the different responses obtained with polypropylene and nylon polymers as previously shown. Polypropylene has very little affinity for the glass surface. The glass reinforcement, therefore, requires chemical bonding agents and very high coupling site density. This is accomplished by increasing the fiberglass surface area to allow maximum glass-polymer bonding.

Nylon, on the other hand, contributes to the overall interface bonding through its chemical functional groups.

2-6 EFFECT OF PROCESSING CHARACTERISTICS ON COMPOSITES

2-6.1 MIXING TIME

Table 2-18 gives the effect of mixing time on the tensile and flexural properties of various 25% glass-reinforced polystyrene formulations. All glass reinforcements were coated with a poly (vinyl alcohol) size and an A-1100 silane coupling agent. These results indicate that increasing mix times results in a decrease in tensile and flexural strengths but has only a marginal effect on flexural modulus.

The aspect ratios of the samples tested ranged from 150 at the low mixing times and high integrity glass to 35 at the 5-min mixing time for samples B and D. This parallels the drop in strength properties.

The results also show that the very high integrity glass gives marginally better properties over the high integrity glass, and the properties fall as the integrity is reduced.

The best glass reinforcement for both the Brabender mixed polystyrene and the Brabender mixed and injection molding compounded polypropylene was a high integrity strand with 408 filaments of a 10- μ m diameter, 1/4 in. or 1/8 in. long²².

Glass variables were not as important for nylon 6 due to the low melt viscosity of the polymer. This reduces the shear stresses on the glass strand and lowers the rate of dispersion of the glass. However, Ref. 22 reports that marginally superior results were obtained with HI/408/10 μ m glass fibers.

2-6.2 SCREW SPEED AND BACK PRESSURE

The effects of screw speed and screw-back time

TABLE 2-18. PROPERTIES OF BRABENDER MIXED POLYSTYRENE/GLASS COMPOSITES 25% LOADING W/W (AVERAGE OF AT LEAST FIVE REPLICATES), SIZE - SILANEA-1100²²

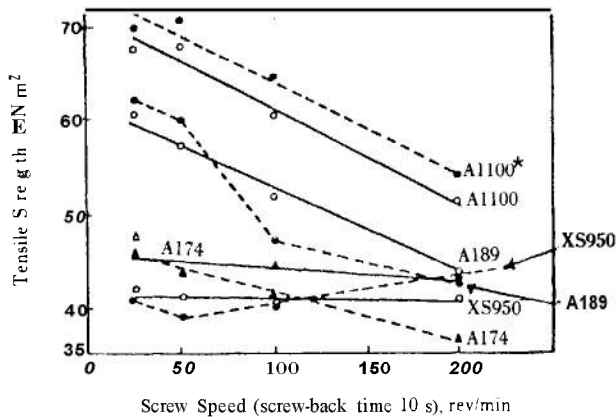
Glass ^a	Property ^b	Mixing Time		
		1 min	2 min	5 min
A: ¼ HI/408/10 μ m	TS	60	58.3	55.2
	FS	05	100	84.8
	FM	5.7	5.7	6.0
B: ¼ MI/408/10 μ m	TS	52.4	48.6	43.8
	FS	02	92.0	85.8
	FM	5.8	6.1	5.8
C: ¼ VHI/408/10 μ m	TS	65.0	64.4	55.6
	FS	06	97.2	89.5
	FM	5.5	5.7	5.6
D: ¼ HI/408/13 μ m	TS	48.9	42.7	43.8
	FS	88.6	82.7	70.3
	FM	5.7	5.9	5.3
E: ¼ HI/102/10 μ m	TS	58.9	56.5	51.0
	FS	94.8	83.4	77.6
	FM	4.7	4.8	5.9
F: ¼ HI/408/10 μ m	TS	66.2	64.5	56.9
	FS	07	99.3	91.0
	FM	5.7	5.7	5.9

^aCoded according to filament length (e.g., ¼ in.); size constant (e.g., HI, highly integrated); number of filaments per strand (e.g., 408); and diameter of filaments (e.g., 10 μ m).

^bTS = tensile strength, MN/m²; FS = flexural strength, MN/m²; FM = flexural modulus, GN/m².

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(plasticization or screw-back pressure) on the properties of directly mixed polypropylene composites with various silane finishes are given in Figs. 2-38 through 2-41. The best silane for optimum tensile and flexural strength was A-1100 under all machine conditions. The other two silanes, A-189 and A-174, were not very effective and, with the exception of A-189 at low screw speeds, were little better than the control glass XS-950 which had no silane treatment. The actual strength values for the different silanes fall rapidly with both increasing screw speed and



*Silane Designation and Chemical Name²²

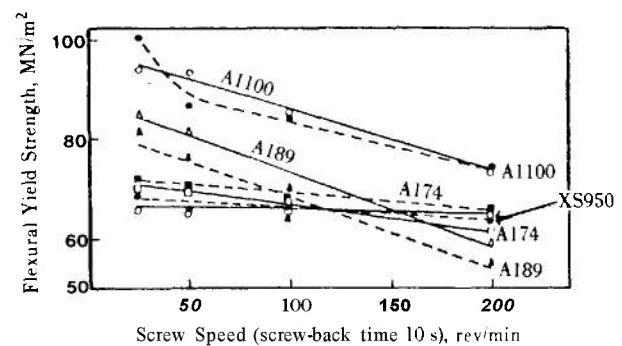
Code	Chemical Name
A172	vinyl-tris(β -methoxyethoxy)silane
A174	γ -methacryloxypropyl-trimethoxy-silane
A1100	γ -aminopropyltriethoxy-silane
A186	β (3,4-epoxycyclohexyl)-ethyltrimethoxy-silane
A187	γ -glycidoxypropyl-trimethoxy-silane
A1120	N- β -(aminoethyl)- γ -aminopropyl-trimethoxy-silane
A189	γ -mercapto-propyl-trimethoxy-silane
XS950	no silane

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Figure 2-38. Tensile Strength vs Screw Speed for Polypropylene/Glass Composites [70% polypropylene GW522M, 30% glass (1/8/HI/408/10 μ m with A1100, A189, and A174 silane finishes; XS950—1/4/HI/13 μ m, no silane finish.) Continuous lines are for dry samples; broken lines are for samples which have been immersed in water at 70°C for one day.]²²

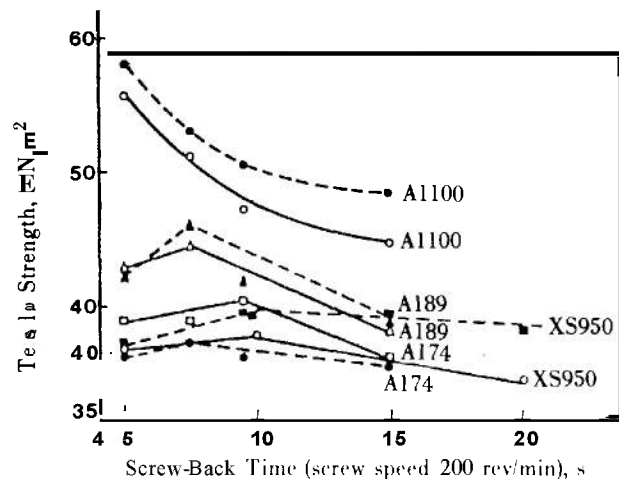
screw-back time thus indicating that for optimum strength, the lowest possible screw speed and screw-back times should be used. In addition, no polypropylene moldings with good appearance were made with any glass treatment at screw speeds of 25 or 50 rev/min although they had maximum strengths. Thus, screw speed is more important than screw-back time in determining the dispersion of fiber bundles. Also, a water soak at 70°C for 24 h had little effect on the strength/processing curves.

Additional testing was done on various polypropylene composites at a screw speed of 200



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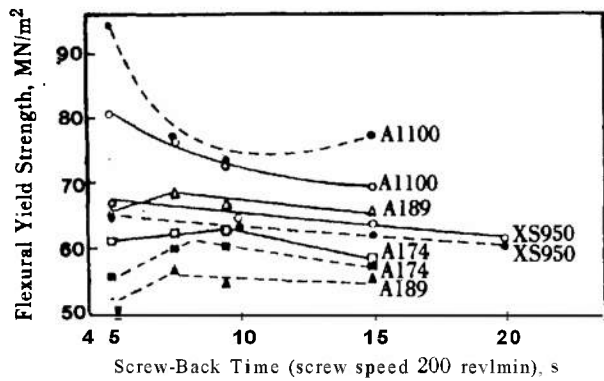
Figure 2-39. Flexural Yield Strength vs Screw Speed for Polypropylene/Glass Composites (Composition of specimens and conditions are the same as for Fig. 2-38.)²²



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Figure 2-40. Tensile Strength vs Screw-Back Time for Polypropylene/Glass Composites (Composition of specimens and conditions are the same as for Fig. 2-38.)²²

rev/min and screw-back time of 10 s which produces visually acceptable moldings. The results are reported in Table 2-19. They show that A-1120 coatings give the best results both wet and dry. The lower results for A-1100 are attributed to the 13- μ m diameter filaments.



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Figure 2-41. Flexural Yield Strength vs Screw-Back Time for Polypropylene/Glass Composites (Composition of specimens and conditions are the same as for Fig. 2-38.)²²

Figs. 2-42 through 2-45 show the tensile strengths of various wet and dry nylon 6 composites with screw speed and screw-back time.

The strengths of dry moldings first decrease and then increase with increasing screw speed and screw-back time. A-1100 glass/nylon 6 molding showed the highest overall strength values when the screw-back time was above 10 s and the screw speed was 200 rev/min. The properties of these moldings are considerably better

than those for ready compounded glass-filled nylon (F-193) which was molded under the same conditions. The F-193 moldings showed little change of property with machine conditions. At lower screw speeds and/or short screw-back times, F-193 moldings gave superior strengths. A-189 and A-174 glass/nylon 6 moldings showed some improvement in properties over the untreated glass XS-950, but these materials are greatly inferior in strength to A-1100 composites. It was not possible to obtain screw-back times greater than 15 s with A-189 or A-174 treated glass. The decline in properties of most composites as the screw speed increased from 25 to 50 rev/min and the screw-back time from 5 to 10 s was attributed to mechanical breakage of the glass fiber bundle without corresponding dispersion of the filaments. (The work on direct molding was carried out with nylon 6 granules¹¹.)

No visually acceptable composites were produced at screw speeds of 25 or 50 rev/min with any nylon 6 formulation tested, whereas acceptable composites were produced at 200 rev/min at most screw-back times.

The A-1100 glass/nylon 6 composites showed a greater percentage change in strength after water soak than the F-193. Only at the highest screw speed and screw-back times did the direct blend material show superior properties. The performances of water-soaked A-189 and A-174 were reversed, and the A-189 composites showed values close to the untreated glass composites.

Glass Coating	Tensile Strength, MN/m ²		Flexural Yield Strength, MN/m ²		Flexural (tan) Modulus, GN/m ²		Strain at Yield, %	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
A-172	46.2	43.5	64.9	63.7	4.8	4.6	2.1	2.9
A-189	45.1	45.2	63.8	63.3	5.4	5.2	1.9	2.4
A-186	45.1	43.3	63.2	63.5	5.1	5.1	3.1	3.2
A-1120	48.5	51.3	69.2	73.3	5.4	4.9	1.8	2.1
A-187	45.4	43.6	68.1	64.0	5.3	4.8	2.5	3.3
A-1100'	44.2	—	70.9	—	5.3	—	2.4	—
XS-950 (nosilane) ^a	35.8	36.5	59.0 ^b	58.9	5.3	4.6	—	4.4

^bStress at 5% strain

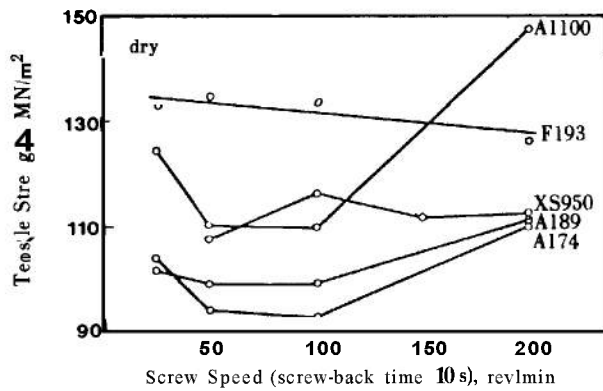
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The property data of additional direct-compounded nylon composites with 200 rev/min screw speed and 15 s screw-back time are given in Table 2-20. The results of these visually acceptable moldings indicate that silane A-1120 coated glass behaves similarly to A-1100, and that A-186

may be a suitable alternative to A-1100 coated glass.

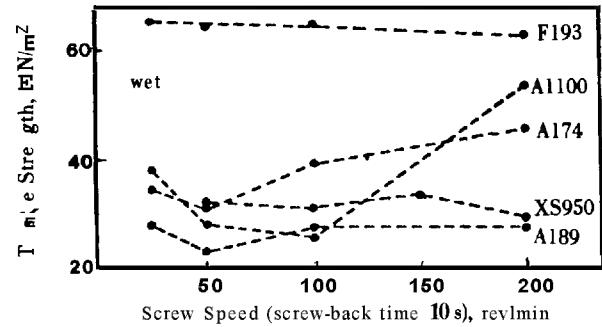
2-7 COMPOUNDING

There are three basic methods for making



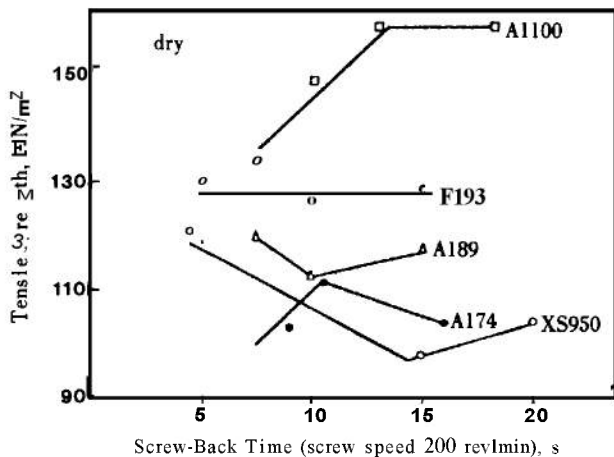
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Figure 242. Tensile Strength vs Screw Speed for Dry Nylon 6/Glass Composites [70% nylon f114, 30% glass (1/8/HI/408/10 μm with A1100, A189, and A174 silane finishes; XS950 – 1/4/HI/408/13 pm, no silane finish.)]²²



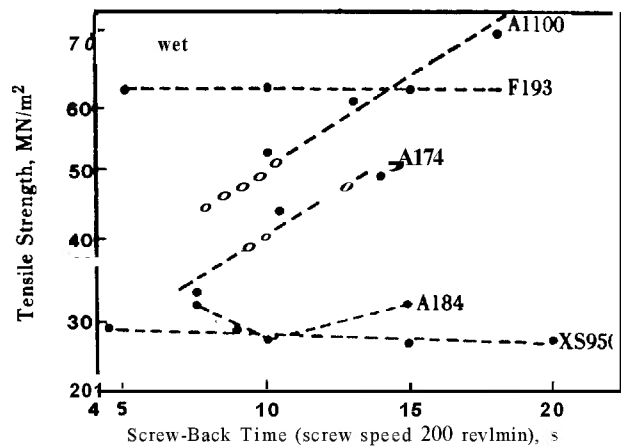
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Figure 244. Tensile Strength vs Screw Speed for Wet Nylon 6/Glass Composites (Composition of specimens as for Fig. 2-42)²²



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Figure 243. Tensile Strength vs Screw-Back Time for Dry Nylon 6/Glass Composites (Composition of specimens as for Fig. 2-42)²²



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Figure 2-45. Tensile Strength vs Screw-Back Time for Wet Nylon 6/Glass Composites (Composition of specimens as for Fig. 2-42)²²

TABLE 2-20. DIRECT BLEND GLASS/NYLON 6 (SCREW SPEED 200 rev/min, SCREW BACK TIME 15 s)²²

Silane	Tensile Strength, MN/m ²		Flexural Strength, MN/m ²		Flexural (tan) Modulus, GN/m ²		Strain at Break or Yield, %	
	Dry	Wet	Dry	Wet	Dry	Wet ^a	Dry	Wet
A-189								
25 rev/min	11.3	—	16.6	—	8.2	—	2.3	—
100 rev/min	12.1	—	16.3	—	8.3	—	2.3	—
200 rev/min	12.0	2.63 ^b	16.2	4.5	7.4	3.2	3.3	—
A-1120								
25 rev/min	15.5	—	21.8	—	7.7	—	3.3	—
100 rev/min	15.4	—	21.7	—	7.9	—	3.7	—
200 rev/min	16.6	6.36	23.8	9.3	7.9	3.9	3.8	4.0
A-172	15.3	6.85	22.7	10.3	8.3	4.0	4.2	—
A-186	16.5	7.87	24.1	11.4	8.3	4.4	3.4	—
A-187	15.4	6.42	21.4	9.0	7.0	4.3	2.8	3.9

^aStress at 5% strain^bYield stress

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glass-reinforced parts: direct feeding of polymer and glass into injection molding machine, direct feeding of a polymer-glass preblend into injection or extrusion machine, and molding precompounded pellets. Each process has its advantages and disadvantages. Also, the compounding process can adversely affect end product properties as shown in Table 2-21. In addition, each formulation has its own problems. The different rheological properties of the various resin systems require distinct melt conditions which relate to the screw parameters used in the compounding system. Temperature uniformity and degree of mixing are also critical conditions related to each specific formulation.^{23,24}

2-7.1 COMPOUNDING PROCESSES

The equipment for production compounding of glass-filled thermoplastics should possess:

1. Steady-state running conditions
2. Reproducibility of processing conditions
3. Easy cleaning
4. Versatility to adopt to new formulations
5. Ability to generate high enough internal shear stresses to facilitate good dispersion of all additives and glass fibers

6. Capability to expose each particle to short and equal stresses

7. Exact temperature control to regulate and minimize heat history.

2-7.1.1 Direct Compounding in an Injection Machine

In this process resin and glass are fed separately into a hopper, and the glass/resin ratio can be varied. Glass content can be as high as 35%. Usually, chopped glass fiber is used, but Dow Chemical Company, for example, has developed a process where roving is used and the glass is chopped above the hopper of an injection molding machine. Direct compounding in an injection machine has some limitations however because it cannot be used over the entire range of thermoplastic materials. It is used primarily with SAN, polystyrene, and the polyolefins²³.

2-7.1.2 Compounding Preblended Material

Preblending chopped glass fiber with polymers prior to extrusion of pellets or in direct injection molding is well-known and widely used in the industry. This process in injection molding pro-

TABLE 2-21. MECHANICAL PROPERTIES OF FIBERGLASS-FILLED POLYPROPYLENE, EFFECT OF COMPOUNDING METHOD^{2,3}

	COMPOUNDING TECHNIQUE					
	Single-Screw Extruder	Continuous Mixer	Direct Molding	Twin-Screw Compounder 1	Twin-Screw Compounder 2	Twin-Screw Compounder 3
Wt % Glass Fiber	25	25	24	25	23	27
Type of Fibers	1/4 in. Chopped Glass	1/4 in. Chopped Glass	1/4 in. Chopped Glass	Roving	Roving	Roving
Tensile Strength, psi	5400	4700	7000	4900	5800	7700
Flexural Modulus, psi x 10 ³	470	460	700	600	555	700
Izod Impact, ft • lb/in. notched	1.0	0.7	2.2	0.9	1.1	1.4
Heat-Deflection Temperature at 264 psi, ° F	206	153	220	203	184	265
Fibers Smaller Than 0.5 mm, %	—	—	—	—	—	29
REMARKS		Glass was fed into the feed section		Screw with very strong sections after addition of glass	Moderate screw after addition of glass	Mild screw after addition of glass (No. 14)

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vides good properties and offers economic advantages, especially where high volume is involved. Normally, only powdered polymers can be used because it is difficult to obtain a good dispersion of fiberglass in the end product with pelletized feed stocks. Glass fiber attrition is minimized with the dry blend technique, but the glass fiber bundles may not be adequately dispersed. The glass fiber bundles can be observed throughout the part in many instances and may produce a very rough surface on the molded part. This technique is not suitable for compression molding parts.

2-7.1.3 Compounding Glass/Polymer Pellets

There are basically two methods of making glass fiber-reinforced thermoplastic pellets—discontinuous and continuous.

2-7.1.3.1 Discontinuous Method

In the discontinuous method only chopped glass is used. High and low shear stresses are developed in this compounding technique, depending on how the glass fiber is blended.

In the high shear process, the polymer and chopped glass are charged into a high intensive mixer, such as a Banbury®, and the blend is compounded. Here, the polymer and glass receive the same shearing action of the rotors. Thus during the melting stage, viscosity is very high, and the glass fiber filaments can be easily broken down to the critical length or even lower.

In the low shear process, the polymer is fluxed, and the chopped fibers are introduced into the melt. The shear stresses in this method are much lower, and longer fiber length can be expected in the final product.

In both these cases, the compound is discharged from an intensive mixer and must be subsequently extruded to obtain the final pelletized material. Total compounding time through the mixer and extrusion system is relatively long. This lengthy contact of the abrasive glass with the machinery can cause abnormal wear of the various internal components. In addition, this process is limited to polymers which do not have a high degree of crystallization, but rather a broad softening range. Polymers which have a sharp melting point cannot be economically processed in this manner²³.

2-7.1.3.2 Continuous Method

There are two methods of producing glass fiber reinforced thermoplastic pellets in the continuous systems—the coating process and the compounding process. The coating process is usually referred to as the Fiberfil[®] process where a cable-coating technique is used. Six to eight strands with about 100-150 individual filaments each are coated with a thermoplastic melt. The coated strand is then cooled and cut into pellets. The length of the fibers is approximately the length of the pellets. The glass in the pellets is not readily dispersed or wetted by the plastic. Also, depending on molding conditions, only about half of the glass is dispersed in the molded item. The remaining is undispersed. This lack of homogeneity creates problems for the production of complicated or thin-walled parts.

The compounding process involves a single or multiscrew extruder. The process can be carried out with either roving or chopped strands. In both cases, homogenization is considerably better than in the coating process. The bundled glass fibers come apart in the machine, and the glass fiber filaments are better wetted by the plastic melt. Volatiles in the compound can affect the wetting of the fibers by the plastic melt. Volatiles consist of air, water, solvents, and monomers contained in the plastic or released from the sizing agents on the glass fibers. This process permits use of equipment with suitable degassing vents for removal of these volatiles after the glass fibers have been added. Some equipment is designed to remove the volatiles after the glass fibers are added downstream into the melt.

The length of the glass fiber is usually shorter in the compounding process than in the coating process. However, it produces a spectrum of

various glass fiber lengths. The width of this spectrum and the average glass fiber length depend mainly on the compounding technique used and on the screw geometry. The melt rheology of the plastic also plays an important role in glass fiber length and glass fiber length distribution during processing.

After compounding, the glass fiber composites are pelletized by strand cutting or by the melt-cutting process. The latter process is especially advantageous in high volume production.

In a continuous system, two essential elements are absolute control over residence time and residence time distribution. The residence time must be short and uniform during compounding to minimize heat history. Machine design, screw rpm, and throughput generally determine residence time. Continuous machines do not have an exact residence time but a residence time spectrum. Uniformity of a continuous operation is determined by the type of spectrum obtained.

2-7.2 EXTRUSION OF GLASS-RESIN PELLETS

2-7.2.1 Single-Screw Extruders

Generally, single-screw extruders use a chopped glass fiber preblend. The preblend is conveyed through all three stages of the extrusion: conveying, compression, and metering. It is during the compression stage, when the polymer melting occurs, that the glass fiber lengths are reduced by the high shear stresses. Usually, a venting section is employed after this stage to remove any volatiles. The material is then pushed through a die. Increasing head pressure damages the glass fiber which affects the properties. Therefore, head pressure must be kept as low as possible.

Glass fiber, chopped or in roving, can be fed separately into the extruder. In this instance, the rotation of the screw must be sufficient to prevent problems resulting from the buildup of the material in the feed pocket. Glass damage can be reduced during the melting stage by using a screw geometry which permits gradual melting from external heat and not solely from mechanical energy input. Wear will occur all along the machine but will differ along the screw length, particularly where the glass fibers are added.

Chopped glass can also be fed downstream into the molten polymer via gravity feeds or metering

equipment through a vent port or side feed unit attached to the barrel.

The screw geometry can be quite different when chopped glass is used instead of roving. The chopped glass only has to be wetted by the polymer, the volatiles removed, and the melt forced through a die. Usually, straight conveying sections are used with various leads. For those polymers that are difficult to homogenize, a small neutral kneading section is incorporated.

The plastic compound can be degased at the same time as the glass fibers are added, by applying a vacuum at any desired point. The compound can also be colored during the same process. The pigments or additives are distributed and dispersed mainly in the plasticizing section, and this is continued in the glass fiber blending zone.

Single-screw extruders do not permit as wide a degree of processing flexibility as twin screws due to the fixed design parameters as screw configuration and L/D ratio.

2-7.2.2 Continuous Mixer Systems

In the continuous mixer system the glass must be in chopped form. The glass fiber and polymer are charged into a continuous rotor where blending results in additional glass breakage. This can be fed into a chamber where the polymer is already molten, thus reducing shear stresses.

2-7.2.3 Twin-Screw Extruders

Twin-screw compounding extruders have intermeshing and corotating screw components. The screws intermesh and clean each other, dead corners are avoided, and the material is forced uniformly through the machine. This results in a thorough mixing of the polymer and glass. Because the screw is built up of individual segments which slide onto the shaft, these segments can vary in length, leads, and lead direction. Special kneading components can also be used to provide different kneading intensities; therefore, it is possible to tailor screw geometries to specific material requirements. Polymers with high melt viscosities or polymers with a high glass loading (40% or higher) require "milder" screw designs than polymers with low melt viscosity or low percentage of glass (30% or less). In addition, small kneading elements or screw elements with reversed flights can be employed to effect the final fiber length distribution. The effect of twin-

screw design on physical properties of glass-reinforced polypropylene is shown in Table 2-21.

Twin-screw extruders use preblends or separate components. The glass can be roving or chopped. The material can be metered into the feed throat or downstream into the melt through a degassing port or side feeder. The equipment is usually stove-fed to prevent segregation when throat fed. These compounders have relatively high screw speeds (200-300 rpm) so they are not limited by the conveying capacity of the screws. Screw speed can be varied independently of polymer feed rate to adjust the glass fiber feed. Roving spools can be set along the machine or placed in creels and pulled into the machine from one end. The geometry of the screw downstream from the roving feed port is largely responsible for the fiber length and the homogeneity of the compound.

2-7.2.4 Specially Designed Extruders

There have been many innovations patented in the design of extruders and extrusion components to improve uneven feeding, conveying, mixing, and temperature control. For example, a new type of compounding extruder (ESK Series) has been patented by Werner & Pfleiderer Corporation which consists of both twin-screw and single-screw sections (see Fig. 2-46).

The feed section of the ESK contains a twin-screw which feeds into a single-screw compounding section. Engineered for complete operational flexibility, the ESK is constructed on the building block principle. The screw and barrel sections are designed so that it is possible to vary the length of the machine.

Also both the twin-screw and single-screw sections have interchangeable components. The screws are made up of individual segments which slide onto the shaft. These segments can vary in length, leads, and lead direction. Special kneading components for different kneading intensities can also be used.

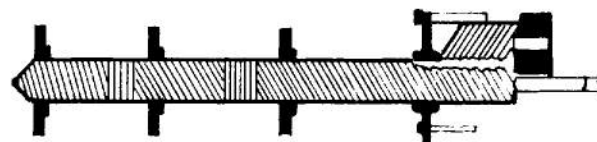


Figure 2-46. ESK Extruder²⁷

This interchangeability of screw components enables the processor to select and assemble the proper screw and kneading block arrangement needed to obtain maximum production efficiency for a specific material or process.

The barrels are also made up of individual sections which are connected by bolts and held in place by support plates. Three types of barrel sections are available: sections with a feed opening, closed sections, and sections with vent-ports.

Additional flexibility is engineered into the twin-screw section. The screws can be selected to be corotating, counterrotating, intermeshing, or nonintermeshing²⁵.

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CHAPTER 3

PROPERTY DATA

Property data for GRTP's are presented in two major breakouts. In the first breakout, the basic resins—styrene acrylonitrile (SAN), polycarbonate, polysulfone, polyacetal, polypropylene, polyphenylene oxide (PPO), nylon, modified PPO, and polyvinyl chloride—are treated as the independent variables; and the physical, mechanical, electrical, thermal, chemical, and weathering characteristics are treated as the dependent variables. In the second breakout, the functional relationships are reversed, i.e., the properties are the independent variable and the resins are the dependent variable. ASTM test methods by which the physical values were determined are listed. The physical data versus resins are presented in both tabular and graphic form.

3-1 INTRODUCTION

The purpose of this chapter is to present property data on GRTP's. The first division of this chapter—pars. 3-2 through 3-6—covers the physical, mechanical, electrical, thermal, chemical, and weathering characteristics of various glass-reinforced resin systems in a comparative fashion. The intent is to familiarize the reader with the ranking of the material in the different properties for resin type consideration. Also discussed are the effects of glass reinforcements on material properties.

The second division—pars. 3-7 through 3-24—presents property data relative to each resin system. Its purpose is to narrow the selection of resin-glass systems into specific commercial formulations for engineering purposes.

3-2 PHYSICAL AND MECHANICAL DATA

Tables 3-1* through 3-22 and Figs. 3-1 through 3-30 compare the physical and mechanical property data of 25 engineering GRTP's as well as the effects of glass reinforcements. The data represent both short- and long-term performance.

3-2.1 SPECIFIC GRAVITY (ASTM D792)

The increase in the specific gravity of glass-reinforced molding compounds as given in Table 3-1 is directly proportional to the amount of glass. Fig. 3-1 shows the specific gravity of nylons 6 and 6/6 with varying amounts of glass. The specific gravities of these nylons are essentially the same.

*NOTE: All figures and tables appear at the end of the chapter.

Polymer systems with the lowest specific gravities are the polypropylenes and polyethylenes; the highest are the fluoroplastics and the acetals.

3-2.2 HARDNESS (ASTM D785 ROCKWELL AND ASTM D2240 DUROMETER)

The hardness, as determined with the Rockwell Hardness Tester, is a measure of the material resistance to indentation by a spherical indenter. The higher the Rockwell hardness number, the harder the material. The scale is given in Table 3-5. The measured property is determined primarily by the elastic modulus of the material. Therefore, the addition of fiberglass increases the hardness, due to the elastic modulus being increased with increasing glass content.

The hardness, as determined with the type D Durometer, is a measure of resistance to indentation by a pointed indenter.

Some of the harder materials are the ABS's, SAN's, nylons, polycarbonates, modified PPO, and polyether sulfones. The softest materials are the polypropylenes, polyurethanes, and fluoropolymers.

3-2.3 WATER ABSORPTION (ASTM D570)

Water absorption of thermoplastic resins is lowered with glass reinforcements as indicated in Table 3-1. Exceptionally low water absorption is found in glass-reinforced (GR) fluoropolymers, PVC, polyethylene, polypropylene, modified polyphenylene oxide, polyphenylene sulfide, polycarbonates, and polyesters. The poorest systems are the nylons 6, 6/6, 6/10; and acetals. Other nylons such as nylons 11, 12, and 6/12 are comparable to

other engineering materials such as ABS, polyether sulfone, and polysulfones.

The changes with moisture content are dependent upon orientation of the glass fibers. The least dimensional change occurs in the direction of fiber orientation; see Fig. 3-2. Slightly more change can be noted in the transverse direction.

The reduction of water absorption for glass-reinforced nylons 6, 6/6, and 6/10 exceeds that expected for simple replacement of the resin by glass fibers. This has been attributed to the greater affinity of the amide groups of the nylon resin for the glass-fiber sizing systems than for water².

The 24-h water absorption of GRTP's at 23° C, as indicated in Table 3-3, ranges from 0.024% for PVC to 0.25% for polyacetal. The saturation (23° C) values range from 0.11% for modified PPO to 1.85% for nylon 6/10. The absorption values in 100° C water exhibit a range from 0.40% for modified PPO to 5.41% for PVC after immersion for 5,000 h. This reverse ranking for short-term versus long-term water absorption for PVC results not only from wetting characteristics but also from the leaching of stabilizers and subsequent replacement with water.

The effect of boiling water on the tensile strength of a series of glass-fortified thermoplastics is presented in Table 3-4. The 30% glass-reinforced PPO, polysulfone, and polypropylene compounds exhibit outstanding long-term hydrolytic resistance in 100° C water, while the 30% glass-fortified nylon 6/10, modified PPO, and PVC exhibit intermediate resistance to 100° C water environment. This test method provides both a hydrolytic attack and an oxidative attack. The oxygen content of the water was maintained by changing it weekly in the test flasks.

In highly permeable resins, a greater degree of hydrolysis takes place along the fibers and wicking occurs. For example, under long-term exposure, 30% glass-reinforced acetal was hydrolyzed to such a degree that the composite had less stability than the unmodified resin. A ranking of long-term hydrolytic aging of a series of 30% glass-reinforced resins tested is polypropylene > polysulfone > PPO > modified PPO > PVC > nylon 6/10 > polyacetal > SAN > polycarbonate.

3-2.4 MOLD SHRINKAGE (ASTM D955)

Mold shrinkage varies with changes in injection

pressure, melt temperature, mold temperature, wall thickness, flow direction, and reinforcement. Shrinkage decreases with increasing injection pressure, melt temperature, mold temperature, and glass reinforcement. It increases with part thickness and gate thickness.

Mold shrinkage of all GRTP's is anisotropic. Shrinkage in the direction of material flow is always less than in the transverse direction. This is due to the orientation of glass fibers in the material. The glass fibers tend to align themselves in the direction that the material is moving, and when solidification occurs, the glass fibers inhibit the shrinkage of the material in this direction.

Of all the variables, wall thickness has the most significant effect on mold shrinkage. More specific data on mold shrinkage are available in Chapter 5, "Processing".

3-2.5 STRENGTH AND RIGIDITY

Plastics are viscoelastic. Their behavior is partly elastic and partly that of a very viscous fluid. Properties of strength and rigidity vary with amount of stress, the rate of loading, and the temperature at which the stress is applied. Viscoelastic behavior requires performance tests to measure time dependence. The viscoelasticity of plastics also severely limits the usefulness of many short-time tests such as impact, tensile, and flexural strengths; and modulus. Unfortunately, such test data are very widespread because they are easier and cheaper to obtain than time- and temperature-dependent information. These data can cause much confusion and disappointment when used for plastics. Short-time data are useful for quality control and specification purposes, and if properly interpreted, can shed some light on plastic performance. However, they cannot be used in design and are more often than not misleading because they do not account for the viscoelastic behavior of plastics.

3-2.5.1 Tensile Strength

Tensile strengths (ASTM D638) in Table 3-1 ranged from a low of 3,000 psi for 25% glass-reinforced FEP to 33,000 psi for 60% glass-filled nylon 6/6. The glass reinforcement improved all tensile strengths with the acetals, nylons, polycarbonate, polysulfone, PVC, and polyester resins being increased significantly. Tensile strengths

as a function of glass contents are presented in pars. 3-7 through 3-24.

Table 3-2 compares the tensile stress of twelve glass-reinforced resin systems and three long glass-reinforced thermoplastic resins. ASTM D1866 type L specimens were chosen. The ultimate tensile stress of all glass-reinforced systems increased with the increasing load rate.

The glass-reinforced polyurethane, PVC, and polyester resins had the greatest rate sensitivity, while the glass-reinforced polystyrene, SAN, polycarbonate, polysulfone, and nylon 6/6 resins had the least.

The long glass-reinforced thermoplastic resins generally exhibit lower ultimate tensile stress values as a function of straining rate than do the corresponding shorter length glass-fiber reinforced resins.

Work-to-break for twelve different GRTP systems and several long glass systems as a function of speed-of-loading is shown in Figs. 3-3 through 3-9.

All GRTP resins exhibited an increase in work-to-break with increasing rate-of-straining except for 30% glass-reinforced polypropylene. The long glass polycarbonate, nylon 6, and nylon 6/6 resins exhibited lower work-to-break values over the entire range of test speeds than the corresponding shorter glass length reinforced resins.

The glass-reinforced nylon 6/10, nylon 6, nylon 6/6, polycarbonate, and polysulfone resins had the greatest straining rate sensitivity.

The 30% glass-reinforced polypropylene resin has a unique decrease of approximately 25% in work-to-break with increasing test speed above the 0.05 in./min range (Fig. 3-4). An extremely large work-to-break value is demonstrated by the 40% glass-reinforced polyurethane resin (55D Shore Durometer Hardness Base Resin) at the 0.05 in./min straining rate (Fig. 3-9).

The effect of temperature on tensile strength is shown in Figs. 3-10 and 3-11. Fig. 3-11 clearly shows the improvement of tensile strength at higher temperatures of glass-reinforced systems over the nonreinforced counterparts. In both cases the 30% Noryl performs well.

Tensile creep also provides a realistic assessment of strength. It is particularly valuable at elevated temperatures where failure of parts under load by creep rupture is a real possibility. Creep rupture is failure by breaking that occurs with time after a material has been placed under constant load, usually at stresses well below the

short-time tensile strength. The rupture may be either ductile, through yielding and drawing; or nonductile, i.e., sudden and catastrophic.

Creep rupture tests are the only valid criteria for determining the strength of reinforced plastics. The stress-strain rupture properties, such as tensile strength and flexural strength, do not predict long-term rupture performance and do not necessarily rank materials in the right order with respect to end-use performance. Examples of the improvement of tensile creep with glass reinforcement are presented in pars. 3-8 through 3-24.

3-2.5.2 Flexural Strength (ASTMD790)

Flexural strengths of GRTP resins in Table 3-1 follow the same pattern as tensile strengths although they are generally 40-50% higher. The static stress-strain rupture properties such as flexural strength do not predict long-term performance and do not necessarily rank materials in the same order as time-dependent studies. Property data detailing the effects of temperature, humidity, and time on flexural performance are presented in pars. 3-8 through 3-24.

Figs. 3-12 through 3-19 compare the flexural creep of various 30% glass-reinforced systems at 73° F and 2000, 2500, and 5000 psi stress. As with nonreinforced plastics, there is a marked sensitivity of creep to variables of temperature and stress.

3-2.5.3 Shear Strength (ASTMD732)

The punch-type of shear shown in Table 3-1 for reinforced systems generally yields results approximating the tensile yield strength (ASTM D638) values for unreinforced thermoplastic resins. The lower tensile elongation and increased notch sensitivity of the glass-reinforced thermoplastic materials apparently contribute to limit the increases in shear strength below the large increases noted in other tensile related properties for reinforced thermoplastics.

3-2.5.4 Composite Strength

The prediction of composite strength is far less developed than the prediction of stiffness. Nevertheless, a reasonable first approximation has been obtained by using the old-fashioned netting analysis. The axial strength of an aligned com-

posite is assumed to be given by the rule of mixtures modified to take into account the fiber length. The composite transverse and shear strengths are assumed equal to the tensile and shear strength of the matrix. The composite strength in any direction other than along the principal axis is given by the maximum distortional work criterion of failure. For a random-fiber composite the strength is then assumed to be equal to the average of the strengths at all angles in a unidirectional composite.

The experimental values of GRTP's fall between the predictions for aligned fibers and random fibers⁶. This is attributed in Ref. 6 to the fact that the experimental values were obtained on end-gated injection-molded tensile specimens in which there was some degree of fiber orientation. Therefore, the strength of a reinforced thermoplastic system was estimated by taking a value midway between the predicted values for a fully aligned and a completely random composite⁶.

3-2.5.5 Impact Strength

Impact strengths are measured by several methods. The Izod impact strength test (ASTM D256) and Charpy tests measure the energy to break a standard test specimen in cantilevered flexure under stipulated conditions of specimen mounting, notching, and rate of loading. The tensile impact strength test (ASTM D1822) measures the energy-to-fracture standard test specimens under stipulated conditions. Drop-weight impact tests simulate a type of impact stress found in applications because they consider velocity as well as energy at impact. Data on Izod notched and unnotched impact strengths as well as tensile impact strengths for GRTP's are shown in Table 3-1. Work-to-break data are shown in Figs. 3-3 through 3-9.

All impact tests suffer from some weaknesses. Izod impact sums all the energy required to break the specimen, including those to bend, draw, and tear resin and fibers. Other notched specimen pendulum tests such as the Charpy test also suffer from most of the same limitations. Tensile impact tests which use unnotched specimens are considered only slightly better⁷.

The notch used in both the Izod and Charpy tests produces a severe stress concentration. For example, the standard Izod notch of 0.01 in. is sharp enough to be considered an artificial crack. Therefore, the energy measured in these stan-

dard tests reflects the resistance of the plastic to propagating a crack.

Drop-weight testing has two main problems. First, the test is a go or no-go type; therefore, a large number of specimens are required to obtain a numerical test value. Secondly, the criteria for failure are more difficult to define. However, with proper equipment designed to minimize data scatter, drop-weight testing offers a single impact test that can rank materials with respect to probable impact performance in a large number of end uses. The criteria for failure can be defined in many ways—such as energy to initiate a visible crack, energy to produce a specific deformation (for ductile materials), or energy to shatter or produce a hole through a particular specimen.

GRTP's normally fail in a brittle manner. Therefore, the energy to initiate a crack is the most meaningful to the designer or end user.

To improve the go or no-go data of standard drop-weight tests and the single speed limitations of simple impact testers, high-speed testers have been developed. These apply shock loads to specimens over a range of speeds. This type of tester has the advantages of the drop-weight tests and produces test data in the form of load-displacement curves. These curves can then be converted into stress-strain curves. The test data can also provide strength at crack or yield, energy to crack or yield, and modulus—all as a function of speed and temperature⁷.

The usual variables in impact strengths—such as resin system, specimen geometry, notch radius, molding condition, straining rate, and magnitude of applied load—are further complicated in GRTP polymers by the average fiber length and length distribution, coupling agent used, fiberglass loading level, and dispersion of glass fibers.

A comparison of notched and unnotched Izod impact strengths is given in Table 3-1.

The superior performance of 25% glass-reinforced PVC, 30% glass-reinforced polystyrene in unnotched Izod impact strength, and tensile-impact values (Table 3-1), when compared to work-to-break values at various loading speeds (Figs. 3-5 and 3-9), demonstrate the weakness of the notched Izod test for comparing the toughness of these materials.

The data in Table 3-1 indicate that increased notched Izod impact strengths are attained with glass-reinforced nylons 6, 6/6, and 6/10; SAN; polyesters; polysulfone; PVC; polycarbonate; and

polyphenylene sulfide. Decreased strengths are obtained with many other systems such as polyacetal, FEP, and polyurethane.

The unnotched Izod impact strengths of thermoplastic resins are generally reduced by the addition of glass fibers. Also, the addition of flame-retardants usually results in decreased impact strength. The glass-reinforced nylon, polycarbonate, and polyurethane resins are regarded as the toughest of the reinforced thermoplastic resins.

A comparison of long glass versus standard glass reinforcements indicates that the long glass specimens have superior notched Izod impact strength; but inferior unnotched Izod impact strength, tensile impact strength, and work-to-break values in tension at all loading speeds.

Glass-reinforced nylon resins, equilibrium moisture-conditioned at 50% RH, have yielded up to a 40% increase in notched Izod impact strength when compared to the corresponding dry-as-molded specimens¹.

A relative ranking of the unnotched Izod impact strength for glass-reinforced thermoplastic resins in Table 3-1 follows: Polyurethane > Nylon 6/10 > Nylon 6 > Nylon 6/6 > Polysulfone > Polyester > PVC > Polyethylene > Polypropylene > SAN > Polystyrene.

A relative ranking of the tensile-strength for the same glass-reinforced resin systems follows:

Polyurethane = Nylon 6/10 > Nylon 6/6
> Polycarbonate > Polysulfone > Polyester
> PVC > Polyethylene > Polypropylene
> SAN > Polystyrene.

If impact plays a critical role in an application, then prototype testing is a must as exemplified by the previous discussion.

3-2.6 RIGIDITY (ASTM D638 and D790)

Tensile and flexural moduli of thermoplastics are dramatically increased with glass reinforcement as shown in Table 3-1. Three- to five-fold increases in flexural modulus can be readily obtained in thermoplastic resins with the addition of glass fibers. Flexural modulus values to 1,300,000 psi can be realized with the addition of 30% glass fibers to 6/6 nylon. The flexural modulus data comparison is presented to demonstrate the ability of glass fibers to increase dramatically the rigidity of a series of thermo-

plastic resins. The modulus data in Table 3-1 do not consider the effects of time, temperature, and straining rate on long-term rigidity. These data are generally available for most of the reinforced resin systems presented.

Fig. 3-20 compares the flexural modulus versus temperatures for four 30% GRTP's. Because modulus is a frequently appearing property in mechanical design equations, creep data often are plotted as apparent or creep modulus. These data are shown in Table 3-6 for GRTP's. As can be seen, the apparent creep modulus improves with glass reinforcement. Generally, the creep modulus of the reinforced thermoplastics decreases as stress and temperature are increased. However, the creep modulus data for reinforced nylon, acetal, polyester, polysulfone, and polyvinyl chloride appear to be less dependent on stress under the conditions of this particular test. When creep modulus data at different stresses coincide—a phenomenon known as the Boltzman superposition—there is an obvious reduction in the amount of testing required. However, such a relationship is both temperature and stress dependent, and must be confirmed at the conditions of interest for the specific material involved. Other techniques, such as time-temperature superposition and other empirical correlations, also have been devised to simplify the time-dependent response of plastics¹.

Fig. 3-21 shows the variation of 100-s 0.5% tensile secant modulus with temperature. The results indicate the significant improvement in properties by reinforcing the polymer matrices with glass fibers. The stiffness between reinforced and unreinforced thermoplastics remains fairly constant over the temperature range from 20° to 100° C. The most outstanding thermoplastic material in terms of stiffness is the 30% glass-filled Noryl (J).

An interesting fact, not brought out by single-point testing, is revealed in Fig. 3-22 which shows the variation of the 100-s tensile secant modulus with strain. This indicates that at strains, not high by normal plastics standards, the modulus values of the reinforced materials have dropped considerably. This presumably indicates that the bond between the fibers and the matrix has failed and the material has yielded. Some materials are better than others. These results indicate caution when using reinforced thermoplastics at strains greater than 0.01.

The modulus for an aligned-fiber composite in

the direction of the fibers can be predicted by the Halpin-Tsai equations, taking into account the aspect ratio of the fiber. Such equations tend toward the “rule-of-mixture” equation for large aspect ratios. The major Poisson’s ratio can also be predicted by the rule of mixtures. The modulus transverse to the fibers and the shear modulus are given by the Halpin-Tsai equations fitted to the results developed by Tsai *et al.* for a square array of fibers. In all these equations a time-dependent value of the matrix modulus is used to give a time-dependent predicted value. These principal elastic modulus values are linked together using the transformation equations to give the values at any angle. Finally, the laminate approximation is used to predict the properties of a random-fiber composite⁶.

Experimental results, obtained from testing end-gated injection-molded tensile specimens in which there was some degree of fiber orientation, were estimated with confidence by taking a value midway between the predicted values for a fully aligned and a completely random composite⁶. This is shown in Fig. 3-23.

3-2.7 FATIGUE (ASTMD671)

Under repeated cyclic stress, GRTP’s will fail in time at stresses considerably below their static breaking strength. The number of cycles to failure is usually a characteristic of the material, but depends upon the stress, temperature, cycle rate, and other factors such as glass contact.

The basic mechanisms of fatigue failure in elastic materials such as metals are explained in terms of catastrophic brittle fracture. The hypothesis postulates the initiation of very small cracks near microscopic flaws, voids, or discontinuities at stresses lower than the static breaking strength. Once begun, the crack propagation is promoted by the repeated stress until the cracks become so severe that catastrophic fracture occurs. However, plastics are viscoelastic materials, and their fatigue cannot be wholly explained by this mechanism. Many plastics show ductility in fatigue. A major factor in fatigue of plastics is damping, in which a significant portion of the applied energy is dissipated as heat. This heat rise causes thermal softening.

It has been shown that heat rise during fatigue is directly proportional to the damping capacity of the material. Heat rise is specifically proportional to damping as measured by loss compli-

ance, a fundamental mechanical property of plastics. Thus loss compliance is a measure of energy dissipated as heat under cyclic stressing⁷.

The result of most fatigue testing is the generation of *S-N* curves. These curves plot stress *S* against the number of cycles to failure *N*. The data are obtained by testing many specimens to failure at different stress levels. As with any type of time-dependent strength property, the life to failure increases as the stress is decreased. Also, an endurance limit is reached, i.e., a maximum stress above which the material will not withstand cyclic stress indefinitely. For experimental convenience and time required, fatigue tests are usually discontinued if failure has not occurred by 10 million cycles.

Different types of stress situations are common in fatigue testing—including constant strain, alternating tension and compression, or flexural stress. These stresses may cycle around some preset limit, or they may alternate from a mean stress or strain of zero. These various methods will produce significantly different results in plastics. Therefore, the test conditions should simulate as closely as possible the actual application. Effects of various variables and the ranking of different materials may easily be reversed by choosing different test conditions.

Fig. 3-24 shows *S-N* curves for different materials. In general, GRTP’s as a class of materials have significantly greater fatigue strengths than unreinforced thermoplastics, due to their inherently greater rigidity and lower damping.

Investigations have shown that many factors contribute to the fatigue strength of GRTP’s. The four primary factors are matrix strength and elongation, glass fiber length, and resin-fiber bonding strength. Strong matrix materials and short fiber reinforcements enhance fatigue strengths as well as good bonding strengths.

The propagation of fatigue cracks is controlled by fiber distribution and the toughness of the matrix materials. Fatigue damage initiates in all materials by debonding mechanisms⁷.

3-2.8 WEAR, FRICTION, AND GEAR TOOTH STRENGTH

The addition of glass fibers and polytetrafluoroethylene (TFE) to thermoplastic resins results in composite materials offering high performance capability for gears, bearings, cams,

slides, and ratchets. Table 3-7 compares the wear factor, coefficient of friction, limiting PV , and gear tooth strength of unreinforced and glass-reinforced TFE filled thermoplastics.

3-2.8.1 Limiting Pressure-Velocity (LPV)

The load and velocity capability of each bearing material is expressed by the product of the unit load P (psi), based upon the projected bearing area (in.²), and the linear shaft velocity V (fpm). The symbol PV is used to denote this pressure-velocity relationship.

To determine the LPV for a composition, a sample cylindrical half bearing, usually 1 in. x 1 in. x 0.060 in. wall, is placed in an antifriction bearing mounted in the test apparatus. The antifriction-bearing holder is equipped with a torque arm. A load is then applied through the antifriction bearing to the test bearing. The shaft can be rotated at surface speeds from 10 to 1000 fpm. The load (psi); velocity (fpm); friction torque (lb-ft); and the temperature (° F) at the bearing holder, 0.125 in. from the rubbing surfaces, are monitored continuously. A minimum of three speeds normally are selected to cover a practical range—i.e., 10, 100, and 1000 fpm. At each speed selected a load-stepping test is conducted. Friction torque and bearing temperature, which are plotted continuously, are allowed to reach equilibrium at each loading (see Fig. 3-25).

After the equilibrium condition is maintained for approximately 30 min, the load is increased. At some advanced load increment, the friction torque and/or temperature will not stabilize. The PV product at which it last stabilized is designated the limiting pressure-velocity for that material at that specific velocity. Although results are not transferable to other sample configurations, the test provides information useful for comparing thermoplastic composite systems⁷.

Predicting the effects of the addition of polytetrafluoroethylene (TFE), reinforcing-glass fibers, and combinations of these on the LPV is somewhat difficult. The addition of glass fibers alone at loadings up to 50% generally increases the LPV of a thermoplastic system at all speeds since the coupling of the resin to the glass results in a larger shear energy requirement for removing the resin and the glass itself is a harder bearing material. The increased heat deflection temperature of GRTP's also allows bearings to withstand higher temperature without failure.

The greatest improvement in LPV, however, is always found at lower speeds. It is at low speeds that the PV limit of thermoplastic materials is dependent on their load-carrying ability. The increased modulus and reduced creep of GRTP's allow a greater applied loading before cold-flow occurs¹⁴.

The TFE enhances boundary lubrication, and the LPV is increased at all speeds. At comparable volume loadings, TFE results in higher PV limits than glass fibers. Since only a moderate increase in modulus and creep resistance is obtained, it is primarily by functioning as a boundary lubricant that TFE increases the PV limits. Internally lubricated thermoplastics also excel at high speeds. At 100 fpm, the LPV of nylon 6/6 containing 20% TFE is increased 1300% (Ref. 14).

A synergistic effect results from the addition of both glass fibers and TFE in bearing properties since the deficiencies of both materials are removed. Thus nylon 6/6 with 15% TFE and 30% glass fibers results in an increase of approximately 500% in LPV at all speeds. Since the TFE and glass fiber fillers excel at the extremes of wear (1000 fpm) and load (10 psi), respectively, LPV's at intermediate speeds and loads are generally improved the most (see Table 3-7).

Materials excelling in LPV are polysulfone, nylons, and polyesters.

3-2.8.2 Coefficient of Friction

Frictional force generally is believed to be derived from three major components: (1) the force required to shear welded asperity (high spot) contact areas; (2) the force required to push asperities of one surface through those of the other; and (3) the force needed to overcome cohesive effects between the surfaces of these interlocking "mountains and valleys". Very little force is needed to shear welded contact areas, and any interlocking is also easily sheared or plowed through⁷.

The coefficient of friction data in Table 3-7 were obtained with the thrust washer test apparatus. The test specimen is "run in" against the standard wear ring until 360-deg contact between the raised portion of the thrust washer and wear ring is made. Temperature of the test specimen is then allowed to stabilize at the test conditions (generally 40 psi, 50 ft/min, room temperature, and dry). After thermal equilibrium, the dynamic frictional torque generated is determined with

the torque arm mounted on the antifriction bearing. A minimum of five readings are taken. The dynamic coefficient is then calculated by substituting the average friction torque into Eq. 3-1

$$Cf_d = \frac{P_1}{P_{2d}}, \text{ dimensionless} \quad (3-1)$$

where

Cf_d = dynamic coefficient of friction, dimensionless

P_1 = force based on the area of the raised portion of the thrust washer, lb

P_{2d} = dynamic frictional resisting force based on the friction force generated at the mean diameter of the raised area of the thrust washer, lb.

The static coefficient is the starting friction and is determined as follows:

1. The desired load is applied to the thrust washer specimen.

2. A scale is placed against the torque arm mounted on the antifriction bearing.

3. The torque required to start the bearing in motion is recorded.

4. Five readings are taken and the average reading is used to calculate P_{2s} .

P_{2s} is the static frictional resisting force based on the friction force generated at the mean diameter of the raised portion of the thrust washer.

P_{2s} is then substituted into Eq. 3-2 for the static coefficient of friction Cf_s

$$Cf_s = \frac{P_1}{P_{2s}}, \text{ dimensionless} \quad (3-2)$$

where P_1 again is the force in pounds based on the area of the raised portion of the thrust washer.

Data presented in Table 3-7 categorize gear and bearing performance of various nonreinforced and reinforced systems as well as TFE as an internal lubricant. The prototype test remains the best evaluation tool available to the design engineer and should be used prior to final material selection⁷.

Polytetrafluoroethylene (TFE) has the lowest coefficient of friction (0.04-0.06) of the internal lubricants such as molybdenum disulfide (0.12)

and graphite (0.09) which are incorporated into thermoplastic resins. TFE has a lower static than dynamic coefficient of friction, insuring nonstick-slip properties. TFE requires little shear energy to form a soft continuous film of lubricant. TFE has an extremely low critical surface tension (18.5 dyn/cm) and therefore has high release properties. These factors account for its superior performance in internally lubricated thermoplastics^{8*}.

During break-in wear, TFE particles embedded in the thermoplastic matrix are sheared and form a high lubricity film over the mating surface. Because TFE has an extremely high molecular weight, frictional energy at the wear interface does not effect significant changes in viscosity until temperatures are over 300° C. Oil-based lubricants exhibit dramatic viscosity drop and often degrade at temperatures lower than 300° C (Ref. 14).

The frictional properties of TFE-glass reinforced systems display a low modulus compared to most metals. TFE in many of the modified thermoplastics has a compressive modulus of only 60,000 psi, compared to 30,000,000 psi for mild steel. Metal-thermoplastic friction is characterized by adhesion (metal and plastic cannot weld) and deformation (rather than plowing). This mechanism of friction generation results in a frictional force which is not directly proportional to load. For thermoplastic resins, the coefficient of friction decreases with increasing load. Also, the coefficient of friction of thermoplastics increases with increasing speed due to their decreasing ability to form a creep region around asperities. Thus the differences in frictional characteristics lead reasonably to the conclusion that TFE-glass reinforced systems will have better frictional characteristics than metal¹⁴.

3-2.8.3 Wear

Disagreement among investigators concerning the basic wear property has generally been in interpretation and reporting of raw data. When the data have been reported in a form suitable for comparison, they still cannot be used analytically to predict wear at conditions slightly different from the test reported.

Wear of an unlubricated surface is considered proportional to the load supported multiplied by the distance traveled. Mathematically this is expressed as

$$W \propto FD \quad (3-3)$$

or

$$W \propto FVT \quad (3-4)$$

A factor of proportionality K is introduced to make Eq. 3-4 an equality, i.e.,

$$W = KFVT, \text{ in}^3 \quad (3-5)$$

where

W = volume wear, in³

K = proportionality factor (wear factor),
in³·min/ft·lb·h

F = load, lb

V = velocity, fpm

T = elapsed time, h.

These expressions pertain to volume wear which are of little direct use to the engineer. Radial wear, or change in bearing wall, is of concern. However, if the geometry of a given bearing is known, volume wear can be related to radial wear. For example, the radial wear (r in inches) of a cylindrical fixed bearing loaded unidirectionally is approximately equal to the volume wear (W in cubic inches) divided by the projected area (A in square inches).

The expression, Eq. 3-5, for volume wear can then be modified for this case by dividing each side of the equation by the projected area A , resulting in ⁷

$$r = KPVT, \text{ in.} \quad (3-6)$$

where

$$P = \frac{F}{A}, \text{ psi.} \quad (3-7)$$

If allowable wear and the wear factor of a given compound are known, working PV can be determined.

If the required PV level is established, radial wear per unit time can be predicted. However, because wear rate is affected by the material, finish, and hardness of the rubbing contact surface, and by temperature and environment; gross extrapolation of data obtained is not recommended⁷.

The wear factor is accepted as a means of comparing bearing materials. Wear factor data

reported in Table 3-7 were obtained with a thrust washer test apparatus. In this test, the sample thrust washer is mounted in an antifriction bearing equipped with a torque arm. The test specimen holder is drilled to accept a thermocouple probe. The raised portion of the thrust washer bears against a cold-rolled, carbon-steel wear ring with 12- to 16-pin. finish, 18 to 22 Rockwell "C" scale hardness at room temperature, and dry.

Each test is conducted with a new wear ring which has been cleaned. The weight of the test material is measured on an analytical balance. The bearing surface is cleaned and the specimen inserted in the holder. Bearing temperature and friction torque are continuously measured.

Usually, wear tests are conducted at approximately 50% of the previously established "limiting PV ". Periodic checks are performed at high V -high P , high V -low P , high P -low V , and low P -low V to revalidate the basic wear factor theory, i.e., wear factor is relatively constant if the load-velocity relationship is below the established "limiting PV " curve for the particular material. Excellent correlation of wear factor data has been achieved⁷.

The test duration depends upon the period required to achieve 360-deg contact between the raised portion of the thrust washer and the wear ring. The average wear factor and duration of this break-in period are reported. Reported wear factors for each material are based on equilibrium wear rate independent of break-in wear.

Volume wear W is calculated by Eq. 3-8

$$W = \frac{\text{weight loss}}{1000 \times \text{density}}, \text{ cm}^3 \quad (3-8)$$

where weight loss is in milligrams and density is in g/cm³. This volume is substituted into Eq. 3-5 for calculation of wear factor K .

The reduction of wear and friction upon addition of TFE to thermoplastics is demonstrated in Table 3-8. For example, addition of 20% TFE to nylon 6/6 resulted in a wear reduction of 1700%.

The situation becomes more complicated when a glass reinforcement as well as the TFE are present. The addition of glass fibers results in a reduction of wear over virgin resin. This is shown in Table 3-8 for nylon 6/6 with 10 to 60% glass fibers. The reduction in wear is not as great for 30% glass loading alone as it is for 20% TFE loadings. The addition of TFE to GRTP's usually results in reduction of wear to a level comparable to TFE

alone. The low wear rates of TFE GRTP's coupled with their low coefficients of friction account for their preference to metal forerunners.

The wear factor K for any composite is a function of many variables. Some of the established trends are:

1. For each thermoplastic family there is an optimum ratio between the resin and TFE content.

2. Structural integrity limits the maximum filler content. Therefore, to establish the optimum filler content for a given thermoplastic, a balance of LPV, wear rate, and structural integrity must be determined.

3. Increasing temperature will decrease the LPV and increase the wear rate of glass-reinforced materials containing TFE.

4. Shaft material, surface finish, and hardness drastically affect wear rate.

Wear is a more complex phenomenon than friction. For example, while the coefficient of friction for materials varies over two orders of magnitude, materials with low coefficients of friction can demonstrate high wear (like TFE) and vice versa. Several mechanisms operate in the removal of material from a wear interface, i.e.:

1. Catastrophic decay is the result of severe wear when large fragments are lost due to surface fatigue.

2. In adhesive wear, fine polymer-powder gradually is removed from the mating surface. Adhesive wear is due to the high pressure and intense heating developed during collision of asperities. Under these conditions thermoplastics melt and adhere to the harder surface. If a thermoplastic is mating against itself, asperities will microweld and then break by shearing action. Plowing occurs if one of the mating surfaces is harder than the other, i.e., the asperities of the harder material cut through the softer material. The plowing effect is reduced in thermoplastics, compared to metals, due to plastic flow around plow asperities rather than permanent deformation.

3. Corrosive wear is due to the gradual degradation of the plastic surface through oxidation and chain scission. The embrittled layer is removed quickly at the wear interface. Unlike metals, hydrolytically induced corrosive wear is not a problem in plastics.

4. Lastly, abrasive wear occurs when foreign particles enter the wear interface and abrade one or both surfaces, depending on their hardness.

Thermoplastics mitigate the effect of abrasive particles by two mechanisms: (a) at initial impingement at high angles of incidence the thermoplastic can distribute the stress more readily than a metal because of its lower rigidity, and (b) the particles can be embedded within the plastic below the wear interface¹⁴.

3-2.8.4 Tooth Strength of Gears

Tooth strength was determined on injection molded, 20 pitch, 20-deg pressure angle, full depth, 2.5-in. pitch diameter, 0.5-in. face-width spur gears and 32 pitch, 20-deg pressure angle, full depth, 2.5-in. pitch diameter, 1/8-in. face-width spur gears. A sturtevant torque testing fixture and torque wrench (S-1299-1) were employed to measure the tooth strength values. Three teeth per gear were individually engaged and torqued to failure. The average values for three gears are given in Table 3-7.

A major difficulty associated with tooth strength testing is the variation in applied rate of strain induced by varying molding tolerances due to shrinkage differences, testing rate, and failure modes. No predictable correlation has been observed between tooth strength, tensile strength, and shear strength for the TFE lubricant and GRTP's. Scanning electron microphotographs (SEM) of gear tooth fracture surfaces torqued to failure, of glass-reinforced nylon 6/6, and glass-reinforced acetal reveal significantly different fracture behavior patterns. The glass-reinforced nylon 6/6 compound SEM's indicate strong adhesion of resin particles to the glass fibers while the glass-reinforced acetal compound SEM's indicate essentially no adhesion⁷.

3.3 THERMAL PROPERTIES OF GLASS-REINFORCED THERMOPLASTICS

The increasing demand for thermoplastic composites in varying high temperature applications has resulted in intense interest by material engineers in their thermal properties. Some of the desired requirements for composites are:

1. Ability to withstand short-term exposure to 400° F

2. Less than a 50% loss in properties after exposure to 240° F for 100,000 h

3. Dimensional stability under load at 300° F

4. Ability to maintain engineering properties

(6,000 psi tensile strength, 300,000 psi flexural modulus) at 350° F

5. Ability to demonstrate chemical resistance at elevated temperature

6. A heat deflection temperature at 264 psi exceeding 350° F.

3-3.1 THERMAL STABILITY

The chemical structure of the composite's matrix or resin system, more than the optimization of the glass reinforcement, determines thermal stability; This is attributed to the bond strengths found in their structure. The different bond strengths of some carbon combinations found in polymer systems are shown:

Bond Strengths, kcal/mole			
C H	98.7	C-O	85.5
C-C	82.6	C=O	166-179
C=C	145.8	C-F	116
C-N	72.8	C-Cl	81
C=N	147	C-S	65

3-3.2 THERMAL ANALYSIS

Thermal analytical techniques such as thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) permit assessment of polymers without involved physical testing. In TGA, the weight change is monitored while the temperature is increased at a constant rate. In DSC, the temperature is increased at a constant rate and the amount of heat necessary to maintain a temperature change at a constant rate is measured. Isothermal varieties of these techniques are used where the temperature is held constant and changes noted.

Of the two techniques, DSC is preferred for engineering plastics. Most thermal changes in this method can be related to changes in the physical properties of the polymer in the stable condition. The weight changes observed in TGA usually indicate catastrophic behavior, often after the polymer has lost its strength.

The two most significant thermal transitions monitored in engineering plastics by DSC are the melt point T_m and glass transition T_g temperature. The melt point of crystalline plastics is the

temperature at which the material changes from a solid to a liquid and is considered a first order transition. The T_g temperature is considered a second order transition since it is characterized by a change in coefficient of thermal expansion or heat capacity. The T_g transition is exhibited in amorphous polymers and the amorphous regions in partially crystalline polymers. The degree of crystallinity of polymers thus determines the significance of the T_g ¹¹.

Glass transition indicates the conversion of a polymer from a glassy state to a more fluid state but not a liquid state as in T_m . In amorphous polymers the transition is accompanied with the loss in mechanical properties and ability to be fabricated by melt processing techniques. It indicates the transition from a brittle to a tough material in crystalline materials.

In GRTP's the polymer matrix transfers the load to the glass fibers which results in improved load-bearing capabilities. Therefore, in short-term, high heat applications, strength should be maintained up to the T_m and T_g temperatures. Systems which are chemically coupled — such as nylon, PPS, polyester, and polysulfone — display the ability to bear short-term loads up to the transition temperature. Systems which are not optimally coupled do not approach the transition temperature as closely". This is reflected in the deflection under load (DUL) data in Table 3-9.

Tensile strength at higher temperatures is improved by glass reinforcement as shown in Table 3-10. Thermal properties are more dependent on the resin system than on the glass reinforcement. For example, the thermal analysis data in Table 3-11 shows polysulfone undergoes a thermal transition at 281° F. This is accompanied by a drastic reduction in tensile strength from 14,900 psi at 200° F to 2,300 psi at 300° F. The amorphous regions of nylon 6/6 undergo a thermal transition at 138° F. The data in Table 3-10 indicate that between room temperature and the nylon 6/6 melting point, the greatest loss occurs at this transition temperature. If the minor transformation is endothermic (a glass to glass transition or T_g within a crystalline material such as polysulfone), properties will suffer. If the transition is exothermic (crystal to crystal as in PPS and nylon 6/6), properties are not affected as significantly but dimensional changes occur".

The results in Table 3-10 indicate that the amount and rate of tensile strength loss as a function of temperature varies widely. However,

when the tensile strengths of the composites are grouped generically by crystalline or amorphous polymers and are plotted (as in Figs. 3-26 and 3-27), certain trends are evident.

The crystalline systems have an initial rather sharp decrease in strength at 200° to 250° F. This is followed by a more gradual decrease in strength for the next 75 to 100 deg F. Additional increase in temperatures results in losses equal to the initial losses until no effective mechanical properties exist. Although additional test data are needed, it appears that the tensile strength vs elevated temperature curves for most crystalline GRTP resins result in a family of parallel curves. It is assumed that the polyimide exception, which did not exhibit a secondary inflection point, would at temperatures over 450° F (Ref. 11).

The amorphous group also has two distinct changes in strength — a gradual decrease in strength followed by a sharp increase in the rate of loss. Further increases in temperature result in a flattened loss curve; however, over 80 to 90% of room temperature properties have already been lost. This group of polymers also shows a distinct similarity in the slopes of the loss curves¹¹.

Thermal analysis data provide a means for predicting composite performance for short-term exposure to temperatures. This, in conjunction with data derived from mechanical properties at various temperatures, should lead to the selection of appropriate composites for high temperature applications.

3-3.3 LONG-TERM THERMAL PERFORMANCE

3-3.3.1 Long-Term Service Temperature (UL Temperature Index)

The increased use of thermoplastic composites in high-temperature, high-performance applications has necessitated the evaluation of their long-term performance reliability. This is determined by establishing the highest practical continuous-use temperature for the material.

The most widely accepted test method is that used by Underwriters' Laboratories (UL) to determine the temperature index (continuous-use temperature rating) of a plastic material. This test procedure is predicated on a linear time-temperature relationship for the aging of a thermoplastic polymer, i.e., thermal degradation

obeys the Arrhenius reaction-rate equation. The UL test procedure for GRTP's consists of these steps:

1. A polymer is aged at two or more different test temperatures.

2. Reduction of properties caused by thermal degradation is monitored periodically to generate property-degradation curves.

3. The time, at each test temperature, that reduces a physical property to 50% of its original value is then plotted, and an Arrhenius curve is fitted to the data points by regression analysis as illustrated in Fig. 3-28.

A control material with a known index is run concurrently with the material being tested to eliminate effects of test variability. The control material for glass-reinforced composites is usually the base resin.

The Arrhenius curve obtained by this procedure can be used to predict the property half-life of the polymer at a given temperature. The UL temperature index (continuous-use temperature) is determined by the interrelationship of the curves for the control and for the composite being indexed. The continuous-use temperature can be determined by dropping a vertical line from the intersection of the 100,000-h line and the Arrhenius curve (see Fig. 3-28). Since most applications are designed with a life safety factor of 2, a part molded from an indexed compound will still meet minimum requirements of the application after 100,000-h exposure at the rated temperature².

Studies indicate that thermal degradation is caused primarily by free radical chain scission and cross-linking of the polymer molecules close to the surface. This mechanism produces a low-molecular-weight resin on the surface of the part which embrittles and weakens the composite².

Tensile impact strength is affected most by this phenomenon and usually reaches half-life before any other property. The temperature index of a composite generally is controlled by tensile impact strength. Therefore, higher temperature indexes may be acceptable if the material is to be used in applications where impact strength is not critical².

Thermal-degradation data (see specific material and Table 3-9) indicate that the GRTP's retain a greater percentage of the original property at a given time and temperature than does the unreinforced base resin.

The glass-reinforced polyesters, polycarbon-

ates, polyphenylene sulfide, polysulfone, and nylon 6/6 are among the highest long-term service temperature composites.

3-3.3.2 Thermal Aging

Tables 3-12 and 3-13 present tensile strength data on thermally aged composites at 400° F and 500° F. These temperatures exceed those normally used in UL long-term temperature indexing.

The reinforced thermoplastic polyimide, fluorinated ethylene-propylene, and ethylene-tetrafluoroethylene exhibited little or no tensile strength loss after 1500 h at 400° F. The tensile strength of the remaining composites ranged from a loss of measurable strength to a 30% reduction. Their ranking is as follows: polyphenylene sulfide (30%) > polyethersulfone (50%) > nylon 6/6 (61%) > polyester (77%).

The reinforced polysulfone resin exhibited a 50% loss in tensile strength after only 250 h at 400° F. However, it enjoys the highest UL thermal index listing for a thermoplastic resin (Table 3-9). This apparent anomaly is a consequence of employing a test temperature (400° F) exceeding the glass transition temperature (374° F) of polysulfone resin".

The thermoplastic polyimide had less than a 15% loss in tensile strength after 1500 h at 500° F. The polyphenylene sulfide (40% loss) and the polyethersulfone (54% loss) exhibited outstanding thermal resistance at 500° F, considering their rather ordinary performance at the 400° F test temperature. The ethylene-tetrafluoroethylene had an 80% loss after 1500 h at 500° F. The polyester and polysulfone distorted severely at 500° F and had to be removed".

UL continuous-use temperature of polyphenylene sulfide is 355° F when aged at 500° F, and 300° F when aged at 400° F. The UL continuous-use temperature of polyethersulfone at 500° F aging is 345° F, and 300° F at 400° F. Therefore, caution must be used when considering long-term thermal aging results. Some of the hypotheses which have been advanced to explain these anomalies are:

1. The predominance of cross-linking over chain scission reactions results in increased tensile strength.

2. The formation of a dense, cross-linked "skin" results in decreased oxygen penetrability and a greater tensile strength than expected for a given test period".

3-3.4 DEFLECTION TEMPERATURE UNDER LOAD (DTUL)(ASTM D648)

An accepted criterion for describing high-temperature performance of a plastic is the deflection temperature under load (DTUL). This is based on a short-term test that identifies the temperature at which a polymer distorts beyond acceptable limits. It has the limitation of not being able to predict long-term behavior but is a convenient method by which to compare materials.

The common heat distortion test is made in flexure with a test specimen (5 in. x 1/2 in. x 1/2 in.) supported at two points with a 4-in. span. The load is either 66 psi or 264 psi and is applied at the midpoint of the test specimen. The specimen is placed in a liquid silicone bath which is heated at a rate of 2 deg C per min. The heat distortion temperature is that temperature at which the test specimen has deformed 0.010 in.

All thermoplastics improve in DTUL upon the addition of glass-fiber reinforcement. The degree of improvement varies with the resin system. For example, with 20% glass fiber polystyrene is improved about 20 deg F, and high-density polyethylene by 140 deg F at 264 psi. With 30% glass reinforcement nylon 6/6 is improved by 330 deg F at 264 psi. Such varying responses to glass fiber for different polymers are difficult to explain. However, two conclusions regarding DTUL effects in reinforced thermoplastics can be made:

1. Amorphous polymers are improved marginally. The improvement is approximately 20 deg F at the 20% reinforcement level.

2. Crystalline polymers show exceptional improvement with glass reinforcement. In most cases the DTUL approaches the melting point of the base resin. The typical effect for various polymers is shown in Table 3-14¹².

The change in DTUL with glass content is shown in Fig. 3-29. The maximum improvement occurs at 20% by weight of glass for both amorphous and crystalline polymers.

The difference in amorphous and crystalline glass-reinforced systems DTUL's is attributed to the glass-transition temperature of amorphous polymers and the melting point of crystalline polymers. Table 3-15 shows the relationship of glass-transition temperature of the base polymer to the glass-fiber composite DTUL at 20% by weight of glass. As shown, the modest improvement in DTUL of amorphous polymers is related

to the proximity of the DTUL of the resin to its glass-transition temperature. Furthermore, the glass-transition temperature represents a natural limit for the DTUL of the composite.

The relationship between DTUL of glass-fiber composites based on crystalline polymers and the resin melting point is shown in Table 3-16. For all the systems shown, the DTUL of the reinforced polymer is quite close to the melting point of the resin. The greatest differences exist for polypropylene and polyethylene-terephthalate. For polypropylene, this can be related to percent crystallinity¹².

This discussion of DTUL in relation to resin properties does not explain why crystalline materials respond so well. It has been suggested that the type of crystallinity in the reinforced system, not the percentage crystallinity, is different in the unreinforced polymer. It is also recognized that the reinforcement must be glass fiber to get maximum performance¹².

3-3.5 COEFFICIENT OF THERMAL EXPANSION (ASTMD696)

Another criterion in choosing materials to perform at elevated temperatures is dimensional stability. This is important because parts designed to meet a certain temperature requirement invariably are not used only at that temperature. Temperature cycling to some extent is also involved. This can create problems with materials having a high linear coefficient of thermal expansion. Also, even if a part is designed to operate continuously at some elevated temperature, it will never be assembled at that temperature. Thus, a high coefficient of thermal expansion can lead to problems in bringing a part from assembly temperature to a continuous-service temperature.

Glass fiber is a very effective means of increasing the dimensional stability of thermoplastics. This is illustrated in Fig. 3-30. This particular ABS has a linear coefficient of expansion of 5×10^{-5} in./in.·° F. The addition of 20% glass reduces this to a little below 2×10^{-5} in./in.·° F.

Of the GRTP's, polycarbonate, nylon 6/10 and 6/12, polyesters, modified PPO, polyethylene sulfide, and polysulfone have superior thermal dimensional stability.

3-3.6 FLAMMABILITY

Among the performance requirements of

thermoplastic materials, flammability resistance is receiving considerable attention. Generally, the approach has been to test the finished assembly. These tests, largely coordinated by UL, duplicate the environmental conditions of the actual application. This type of testing is time-consuming and expensive. Therefore, several flammability tests have been developed and accepted that can be conducted on molded test specimens. Results can be used to predict end-use performance. The most widely accepted test methods are:

1. ASTM D635
2. UL Subject 94
3. IBM
4. Oxygen Index.

The procedures and classifications of these test methods are summarized in Table 3-17. This table is a guide to the more commonly recognized tests for measuring flammability and self-extinguishing characteristics of thermoplastics. It is provided for design engineers who may wish to test flame retardant and self-extinguishing materials for special applications.

No plastic materials are entirely noncombustible, nor should standard flammability tests be used to provide a basis for predicting the extent of flame retardancy of plastic materials in actual parts under field conditions which may vary widely from test conditions.

The UL Subject 94 Flammability Test is the most widely used and accepted test of flame retardancy in the plastics industry. When speaking in generalities on flame retardant thermoplastics, an end user or raw material supplier normally is referring to a compound with a UL Subject 94 rating of 94V1 or 94V0. Most application areas require this degree of flame retardancy. The UL Subject 94 Flammability listings are often confused with the UL Temperature Index listings which define the continuous (10 yr) service temperature of the thermoplastic composite. It is, of course, beneficial to have both a UL flame retardant listing and a UL temperature index listing; however, many applications require only the flame retardant listing.

Some thermoplastics such as PVC, polycarbonate, fluorocarbons, and polysulfone are inherently flame resistant but most (styrenics, olefins, and nylons) are not. Since this latter group comprises the low cost resins, much effort has gone into making them more flame resistant by the incorporation of flame-retardant additives.

Such additives normally result in higher costs and inferior properties. These limitations can be modified by using glass reinforcements. Not only do the glass fibers improve physical and mechanical properties; they also increase the flammability resistance of the polymer composite. The glass fiber matrix conducts heat away from the site of combustion and minimizes afterglow which is a limitation in many unreinforced flame-retardant polymers. This characteristic is especially advantageous in horizontal flame tests (ASTM D635) where the entire bar is not surrounded by the hot gases from the burner. The strong glass-to-resin bond also adds integrity to the composite, which minimizes dripping and decreases the burning rate.

3-4 ELECTRICAL PROPERTY DATA

In the selection of polymer systems for electric applications, consideration must be given to the interpretation of the measured values in terms of the part requirement. The material must function over a range of temperatures, moisture, and frequencies found in the environmental and operating conditions.

In general, with the exception of dielectric strength, the electrical properties of polymers are somewhat reduced with glass reinforcement. However, this reduction in many instances is more than compensated for by the added strength, dimensional stability, and high temperature resistance of the material in an electrical application.

3-4.1 VOLUME RESISTIVITY (ASTM D257)

The volume resistivity of a material is the ratio of the potential gradient parallel to the current in the material to the current density. Insulating materials are generally used to insulate and support components of an electric network from each other and from the ground. Therefore, it is desirable to have the insulation resistance as high as possible, consistent with acceptable mechanical, physical, chemical, and thermal properties. Volume resistivity measurements are designed to isolate the inherent properties responsible for the dc insulating qualities of a plastic material. Resistivities above 10^8 ohm•cm are considered to be insulators; those with values of 10^3 to 10^8 ohm•cm are partial conductors.

The volume resistivity data presented in Table 3-18 indicate values from 10^{11} ohm•cm to 10^{18} ohm•cm. The flame-retardant grades exhibit lower volume resistivities than the regular glass reinforced systems.

Polysulfone, polyether sulfone, and modified PPO have the highest volume resistivities. Other GRTP resins can be ranked in the following descending order: polystyrene, polypropylene acetal, PVC, nylon 6/10, polycarbonate, polyester, FEP, nylon 6/6, and nylon 6¹³.

3-4.2 ARC RESISTANCE (ASTM D495)

The dry-arc resistance test measures the ability of a material to withstand the discharge across its surface of an initially intermittent and then continuous high voltage, low current arc.

Experience with the ASTM dry-arc resistance test indicates that the results must be interpreted with caution. The test method is particularly weak in evaluating materials which function in the presence of contaminants or humid environments. The GRTP resins yield arc resistance values ranging from 40-180 s and are ranked in the following order: FEP > polyacetal > nylon 6 > nylon 6/6 > nylon 6/10 > polycarbonate = modified PPO > polysulfone > polypropylene = polystyrene > PVC. The flame-retardant composites are a few seconds greater in arc resistance than the regular glass-reinforced systems¹³.

3-4.3 DIELECTRIC STRENGTH (ASTM D149)

Dielectric strength is the voltage gradient at which a material fails as a dielectric by electrical breakdown. The test results can be affected by temperature, humidity, surface finish, electrode geometry, line transients, rate of voltage increase, surface contamination, and voids. Therefore, (ASTM D149) dielectric strength test data offer the design engineer a rough comparison of thermoplastic composites prepared, conditioned, and tested under similar conditions. The injection-molded 1/8-in. discs of GRTP resins tested (Table 3-18) yield dielectric strengths ranging from 700 V/mil to 300 V/mil. They are ranked as follows: polyethylene > polystyrene = modified PPO > acetal > polyester > polycarbonate = polysulfone > polypropylene = FEP > PVC = nylon 6 = nylon 6/6 = nylon 6/10.

3-4.4 DIELECTRIC CONSTANT (ASTMD150)

The dielectric constant is the ratio of the capacitance of a given configuration of electrodes with the candidate material as the dielectric to the capacitance of the same electrode configuration with a vacuum as the dielectric. The dielectric constant measures the ability of an insulating material to store electrical energy. A high dielectric constant value indicates that the material is capable of storing relatively large amounts of energy. Since the loss of energy from a circuit into an insulator is generally undesirable, the best insulating materials are those having the lowest values of dielectric constant. Many plastics are both frequency and temperature sensitive, and tend to resonate at specific frequencies. Therefore, the electrical properties of plastic insulating materials should be tested over the applicable temperature and frequency range. Glass-reinforced systems are ranked as follows in order of increasing dielectric constant at 60 Hz: polypropylene, FEP, polyethylene, polystyrene, SAN, modified PPO, nylon 12, ABS, polycarbonate, polysulfone, ETFE, polyester, PVC, polyphenylene sulfide, acetal, and nylons.

The dielectric constant of glass-reinforced polystyrene, FEP, polypropylene, polyacetal, and modified PPO resins are relatively unaffected by frequencies of 60-10⁶ Hz. Significant increases in dielectric constant are noted with the addition of flame retardants¹³.

3-4.5 DISSIPATION FACTOR (ASTMD150)

When an alternating voltage is applied to a "perfect" dielectric, current flows so that it is 90 deg out of phase with the voltage. Since no insulating material is perfect, the current actually leads the voltage by something less than 90 deg. The dissipation factor is the tangent of the loss angle. It is also equivalent to the ratio of current dissipated into heat to the current transmitted. Thus, the smaller the dissipation factor, the better the dielectric material.

The dissipation factor of the polymer systems is influenced by temperature, frequency, and contaminants such as moisture.

Glass-reinforced systems which offer the lowest dissipation factors at 60 Hz are polystyrene, polypropylenes, polycarbonates, modified PPO, polysulfone, SAN, FEP, polyester, and polyethersulfone.

Those with the smallest variation in dissipation factor over the 60-10⁶ Hz frequency range are FEP, polyethylene, polystyrene, modified PPO, and the nylons¹³.

The flame-retardant grades generally display increased values of dissipation factor over the frequency range. Additional electrical property data illustrating the effects of temperature, humidity, and frequency are available for many systems described in pars. 3-8 through 3-24.

3.5 CHEMICAL RESISTANCE OF GLASS-REINFORCED THERMOPLASTICS

The chemical resistance of composites cannot be predicted by any simple approach. Also, little experimental data are available in which polymer composites commonly employed in the engineering applications are compared under similar conditions. In addition, no method of applying experimental data obtained for one composite in a given chemical environment has been established for predicting the results of the same chemical environment on a different resin system. The result, from the design engineering viewpoint, has been the sporadic generation of data of little use.

Another difficulty encountered in chemical resistance is the definition of meaningful test parameters. Of those used, weight gain has in general the least utility. Although a large weight increase generally indicates poor chemical resistance, ranking of relative resistance of various polymers by comparing percent weight gains in a chemical environment is of doubtful value. In some instances, a small weight increase is accompanied by swelling of a sample; while in other instances, a large increase is observed without apparent change in properties or appearance².

Changes in weight and in tensile strength of both unstrained and strained unreinforced and glass reinforced polymers at 73° F and 180° F are presented in Tables 3-19 through 3-21.

3-5.1 TENSILE STRENGTH LOSS AND WEIGHT CHANGE

ASTM D-1822 type tensile impact samples were employed to obtain the data in Tables 3-20 and 3-21. Five bars were tested for each chemical environment. A control sample of five bars was also tested and tensile strength calculated. At the end of one week (168 ± 1 h) the test bars were

removed from the chemical environment. The temperature during the test in Tables 3-19 and 3-21 was $23^{\circ} \pm 2^{\circ} \text{C}$. Excess liquid was wiped from the specimens, and the specimens were all weighed and tested within 2 h of removal. Percent weight gain was calculated, and final tensile strength was recorded.

Strained values were obtained by tightening ASTM D1822 type tensile impact bars in an arced jig which applied 0.25% strain. These samples were immersed and removed from the chemical environment with the unstrained samples.

Elevated temperature chemical resistance was obtained by immersing unstrained test bars in the various environments at $81^{\circ} \pm 2^{\circ} \text{C}$ for $72 \pm \frac{1}{2}$ h. If the boiling point of the solvent was below 81°C , the test was run under reflux.

The environmental resistance listed for tensile strength loss in Tables 3-19 and 3-20 includes a tabulation by rank of the resistance of the sample to a particular chemical. The lower the number, the better the chemical resistance. If a composite was observed to have less than 3% loss in tensile strength, it was deemed excellent (E); between 3% and 10%, acceptable (A); between 10% and 25%, fair (F); and over 25%, unacceptable (X)².

In some cases, an increase in tensile strength was observed. This was attributed in part to stress relief. The number of bars exhibiting an increase in tensile strength diminished severely in the specimens which were strained.

The data presented at room temperature for tensile strength change provide chemical resistance at average conditions. These data are applicable where the application only requires that the material support itself. For those composites used in engineering applications, the strength change data at 0.25% strain offer more utility.

A review of the data in Tables 3-19 and 3-20 indicates some general trends. If the chemical resistance of a composite is excellent (E) or acceptable (A) when unstrained, the additional tensile strength loss for the material under strain is generally from 0-5%. Thus, most of the composites judged excellent or acceptable unstrained remain excellent or acceptable strained. However, systems that have marginal (F) or unacceptable (X) resistance generally observe an additional 5-15% tensile loss when strained. Thus, (Table 3-19) a 30% glass-reinforced ABS has excellent resistance to ethylene glycol unstrained with an observed value of 19,080 psi. When subjected to 0.25% strain, a 5% additional loss to

18,070 psi is observed. The same compound is judged unacceptable in methanol with a tensile strength of 13,360 psi. Subjected to 0.25% strain, the additional loss is nearly 50% to 7,600 psi (Ref. 2).

3-5.2 CHEMICAL RESISTANCE

Chemical resistance of composites is attributed to solvent and degradative effects. Careful attention to the parameters associated with solvation, the analysis of empirical test results, and the regard for the special degradative effects observed can permit meaningful predictions of composite chemical resistance. The primary effect of most chemical environments on composites is through their action as a solvent. Solvent effects are determined by polarity and viscosity in conjunction with melting and boiling points and temperatures.

If the polarity of a solvent matches that of a primary polymer bond, the loss in mechanical properties is greater than in other solvents. Thus, a close match represents an incompatible environment for a given polymer system. Selection of a polymer for a given environment should be made by choosing the material farthest from a polarity match with the solvent environment. For example, glass-reinforced nylon 6/6 is resistant to typical cleaning solvents such as carbon tetrachloride, while glass-reinforced polystyrene is unsuitable for exposure to antifreeze (ethylene glycol). Methanol (wood alcohol) of similar polarity but reduced viscosity would be expected to have even a greater deleterious effect on the styrene material. Both of these conclusions are reflected by the data in Tables 3-19 through 3-21².

Also, a pure solvent generally has less effect on a composite than an impure solvent or a mixture of solvents. Gasoline, for example, has a greater effect than hexane².

In almost all cases, GRTP resins have greater chemical resistance than the unreinforced polymer. The mechanical properties of composites far exceed those of the unreinforced polymer. Therefore, even if percent losses in strength were equivalent, the composite would still have a greater strength after exposure. Actually, however, percent strength losses of the composites are generally less than those of the unreinforced polymer².

Systems that are closest to optimum theoretical reinforcement have superior chemical

resistance. Production of such composites involves the physiochemical bonding of the resin to the glass fibers. Thus, the resin is tightly bonded in a composite which does not allow interpenetration of a solvent that could associate more strongly with the resin than the resin associates with the glass².

In general, degradation mechanisms are important in predicting the chemical resistance of polymers only in extreme environments. By the polarity match method, 30% glass-reinforced acetal would be suitable in highly polar environments such as aqueous acids and bases. However, in hot acid of moderate concentration it is unsuitable. This is due to a degradative reaction that is defined chemically as an ether cleavage. Another example is the degradation of 30% glass-reinforced Noryl by oxidizing acids. Dimethyl-sulfoxide, a new aprotic solvent, has greater degradative effects than anticipated on the basis of polarity. This is attributed to the reactions of anionic impurities². Hydrolysis resistance of GRTP's is discussed in par. 3-2.3.

3-6 BACTERIAL AND WEATHER RESISTANCE OF GLASS-REINFORCED THERMOPLASTICS

3-6.1 WEATHER RESISTANCE

Engineering thermoplastic composites are subject to both short-term and long-term outdoor applications. In such applications they are susceptible to moisture, thermal, oxidative, and photochemical (ultraviolet) degradation.

Thermal and photochemical processes result in polymer chain scission and cross-linking. The thermal process proceeds through the lower energy nonbonding orbitals; the photochemical, through high energy antibonding orbitals. Since the photochemical process is predominant in outdoor exposure, it is common practice to block ultraviolet radiation by the addition of carbon black, UV stabilizers, or protection painting the surface of the molded item. The addition of carbon black produces a sharp reduction in the UV degradation but a slight increase in thermal degradation due to the black-body absorption and a slight reduction in mechanical properties.

Samples reported in Tables 3-22 and 3-23 were set in aluminum racks at Malvern, PA, and at Santa Ana, CA. All testing racks were at 45 deg from the horizontal and faced south.

Composites studied were reinforced with 30% fiberglass with the exception of PVC which was 15%. ASTM D638 tensile bars and D256 impact bars were employed. Notches were cut into the impact bars after exposure.

Initial values reported are for specimens conditioned at 50% relative humidity. The initial tensile strength drop for nylons and polycarbonate is not due to weathering since the same drop occurs indoors at ambient conditions.

The data in Table 3-23 indicate that no material lost more than about 5% in tensile strength in one year. Also, the three-month loss was comparable to the loss for the entire year. For example, the tensile strength of polystyrene had California values of 12,350 psi and 12,100 psi for 3 mo and 1 yr, respectively, while the initial strength was 13,600 psi. This behavior is attributed to initial water absorption and formulation of a partially degraded or photooxidized surface which acts as a barrier to prevent further degradation. These effects are quite rapid and would certainly be complete within 3 mo, if not within the first few weeks of exposure².

The increase in tensile strength for polypropylene, polyethylene, and PVC between 3 mo and 1 yr is attributed to stress relief and photochemical cross-linking².

Many variables affect the rate at which samples exposed outdoors will degrade. These include the latitude, angular attitude, and direction of the exposed sample; the UV absorption characteristic of the plastic; the presence of UV stabilizers, pigments, or coatings; the temperature of the exposed material; and moisture and contaminants in the air. Therefore, it is not possible to compare accurately the performance of different plastics exposed at different times, at different sites, or under different angular attitudes. Also, except for very long exposure times, the comparison should be made on the exposure in Langley's (a measurement of radiant energy) instead of days or months. Because of these variations, wherever possible, material should be tested under the exposure conditions of the intended application.

Accurate data on effects of weathering are very time-consuming. An indication of weathering effects can be obtained by accelerated testing via several artificial testing apparatus. Recommended procedures for artificial weathering data can be found in ASTM test methods: ASTM D756, D1499, D1501, D1920, D2565, and G23-69. It

should be noted that none of the artificial weather testing data can be directly correlated to actual outdoor exposure since outdoor conditions are so variable. However, they do present an indication of how a material will withstand outdoor weathering conditions.

3-6.2 MICROBIAL AND FUNGUS RESISTANCE

The resin and glass portions of plastic composites are resistant to microbial and fungous attacks in that they do not serve as a carbon source for nutrition. It is generally the other components such as plasticizers, lubricants, stabilizers, coupling agents, colorants, etc., that support attack. Such attack should be considered when composites are exposed to high temperatures and humidity or soil burial applications.

The effects of such attack are discoloration and loss of light transmission, increased modulus, changes in weight, and deterioration in electrical properties. Recommended test procedures are contained in ASTM G22-67T.

3-7 INTRODUCTION —GLASS-REINFORCED THERMOPLASTIC RESIN SYSTEMS

The purpose of this major paragraph is to give typical property data on specific GRTP resin systems. These data are provided by the material suppliers and represent average results which can be expected. Since materials vary somewhat with different batches, processing techniques, and testing methods, all data should be verified before incorporation in specific design applications. For convenience, the materials have been listed in alphabetical order by resin system, and not by chemical families.

3-8 ACETALS

3-8.1 GENERAL DESCRIPTION

Acetal homopolymers and copolymers are crystalline polymers displaying physical properties that compare with die-cast metal. They are strong, stiff, tough, hard, and have excellent frictional properties over a wide range of temperature, humidity, and solvent exposures.

The inherent anisotropic shrinkage of acetal resin has created close-tolerance molding prob-

lems. However, the addition of fiberglass reduces shrinkage in the flow direction, but fiber orientation can cause dimensional control problems. Special formulations incorporating coupling agents, and selected fibrous and nonfibrous reinforcements have minimized shrinkage permitting close tolerance molding.

3-8.2 PROPERTY DATA

Data are presented in Tables 3-24 through 3-28 and Figs. 3-31 through 3-54.

3-9 ACRYLICS

3-9.1 GENERAL DESCRIPTION

Acrylics are known for their exceptional transparency and weathering characteristics. They also offer exceptional stiffness and intermediate toughness, but applications must be tempered by their fire characteristics and combustibility.

3-9.2 PROPERTY DATA

Data are presented in Tables 3-29 and 3-30.

3-10 ACRYLONITRILE —BUTADIENE —STYRENE (ABS)

3-10.1 GENERAL DESCRIPTION

Glass-reinforced ABS possesses the best balance of properties of the styrene polymer family. They can be formulated for excellent impact and creep resistance. Glass-reinforced ABS formulations for electroplating are also available. These combine platability with improved solvent stress-crack resistance.

3-10.2 PROPERTY DATA

Data are presented in Tables 3-31 through 3-34.

3-11 FLUOROPOLYMERS

3-11.1 GENERAL DESCRIPTION

Fluoropolymers — polyethylene-tetrafluoroethylene (ETFE), polytetrafluoroethylene (PTFE), and chlorotrifluoroethylene (CTFE)—possess outstanding chemical and radiation

resistance coupled with very good dielectric and high temperature characteristics. They are nonflammable; and moisture, abrasion, and weather resistant. The glass reinforcement particularly improves the heat distortion temperature, mold shrinkage, and wear properties.

3-11.2 PROPERTY DATA

Data are presented in Tables 3-35 through 3-37.

3-12 POLYAMIDES (NYLONS)

3-12.1 GENERAL DESCRIPTION

Glass-reinforced polyamides (nylons) are available with various glass concentrations in types 6, 6/6, 6/10, 6/12, 11, and 12. The glass reinforcement (1) increases strength, dimensional stability, deflection temperature, and stiffness; and (2) lowers water absorption while retaining abrasion and solvent resistance. With the exception of nylons 11 and 12, nylons are hydroscopic with moisture absorption influencing their properties and characteristics.

3-12.2 PROPERTY DATA

Data are presented in Tables 3-38 through 3-60 and Figs. 3-55 through 3-79.

3-13 POLYCARBONATE

3-13.1 GENERAL DESCRIPTION

Glass-reinforced polycarbonates combine outstanding toughness with excellent electrical and mechanical characteristics. Glass-fiber reinforcement improves stiffness, creep, and fatigue properties significantly—producing attributes comparable to die casting metals.

3-13.2 PROPERTY DATA

Data are presented in Tables 3-61 through 3-67 and Figs. 3-80 through 3-98.

Polycarbonate is characterized by stability to mineral and organic acids. It is also stable in the presence of water. However, if a part—exposed to a hot water or moist high-temperature environment—is loaded in tension, crazing may be encountered. Embrittlement on long exposure also results. For these reasons a top temperature

limit for such environments of 140° to 160° F is recommended as a practical rule. Polycarbonate is insoluble in aliphatic hydrocarbons, ether, and alcohols; partially soluble in aromatic hydrocarbons; and soluble in chlorinated hydrocarbons. Polycarbonate is slowly decomposed by strong alkaline substances.

3-14. POLYESTERS

3-14.1 GENERAL DESCRIPTION

Glass-reinforced thermoplastic polyesters are a family of high performance engineering plastics designated as polybutylene-terephthalate (PBT), polyethylene terephthalate (PET), and polytetramethylene-terephthalate (PTMT). The trade-names Celanex (Celanese Plastics), Versel (Allied Chemical), and Valox (General Electric) represent PBT's; FR-PET (Tiejin Limited) is a PET; and Tenite/Polyterephthalate (Eastman Chemical Co.) represents PTMT. Their characteristics include dimensional stability, low moisture absorption, high deflection temperature, good chemical resistance, and excellent electrical properties. They are, however, attacked by prolonged immersion in hot water.

3-14.2 PROPERTY DATA

Data are presented in Tables 3-68 through 3-76 and Figs. 3-99 through 3-119.

3-15 POLYETHERSULFONE

3-15.1 GENERAL DESCRIPTION

Glass-reinforced polyethersulfone exhibits outstanding high temperature creep resistance, hydrolysis resistance, and self-extinguishing properties combined with good impact strength and low mold shrinkage.

3-15.2 PROPERTY DATA

Data are presented in Tables 3-77 and 3-78.

3-16 POLYETHYLENE

3-16.1 GENERAL DESCRIPTION

Glass-reinforced high density polyethylene (HDPE) has excellent resistance to water absorp-

tion and chemical attack, and has good dimensional stability and toughness. A high density polyethylene-acrylic acid graft copolymer (PEAG) and polyethylene-acrylic acid interpolymer copolymer (PEAA) have similar properties to the HDPE except that PEAG has substantially improved adhesion to a variety of metal and glass substrates. The properties of unreinforced and glass-reinforced polyethylenes are determined by the material density molecular weight distribution (MWD) and melt flow index.

The band of values shown in Figs. 3-123 to 3-126, 3-129, 3-130, 3-133, 3-135, 3-136, and 3-137 reflects the differences among high density polyethylene—the diluents in density, melt flow, and molecular weight distribution (MWD). In general, while other variables are held constant, a decrease in polyethylene diluent density decreases stiffness, tensile and flexural strength, heat deflection temperature, and elongation. A narrowing of diluent MWD decreases stiffness, tensile and flexural strength, and heat deflection temperature but increases elongation; and a decrease in diluent melt flow increases tensile strength and elongation.

3-16.2 PROPERTY DATA

Data are presented in Tables 3-79 through 3-82 and Figs. 3-120 through 3-141.

3-17 MODIFIED POLYPHENYLENE OXIDE

3-17.1 GENERAL DESCRIPTION

Glass-reinforced modified polyphenylene oxide is a tough, rigid thermoplastic with excellent dielectric properties, high moisture resistance, and dimensional stability.

3-17.2 PROPERTY DATA

Data are presented in Tables 3-83 through 3-85 and Fig. 3-142.

3-18 POLYPHENYLENE SULFIDE

3-18.1 GENERAL DESCRIPTION

Glass-reinforced polyphenylene sulfide is characterized by high temperature stability, excellent chemical and solvent resistance, and self-extinguishing properties.

3-18.2 PROPERTY DATA

Data are presented in Tables 3-86 through 3-89 and Figs. 3-143 through 3-151.

3-19 POLYPROPYLENE AND POLYPROPYLENE COPOLYMERS

3-19.1 GENERAL DESCRIPTION

Polypropylene homopolymers have excellent resistance to heat, water absorption, and chemical attack, but lack dimensional stability at high temperatures and wear properties. Glass-reinforced homopolymers are only marginally superior to unreinforced systems. Glass-reinforced coupled or copolymer polypropylenes have significantly improved strengths and heat deflection temperatures.

3-19.2 PROPERTY DATA

Data are presented in Tables 3-90 through 3-96 and Figs. 3-152 through 3-166.

3-20 POLYSTYRENE

3-20.1 GENERAL DESCRIPTION

Polystyrene properties, depending on formulations, can range from brittle but clear crystal to tough and opaque. Glass reinforcements improve strength, stiffness, and stability.

3-20.2 PROPERTY DATA

Data are presented in Tables 3-97 through 3-99 and Figs. 3-167 and 3-170.

3-21 POLYSULFONES

3-21.1 GENERAL DESCRIPTION

Glass-reinforced polysulfones have excellent mechanical, thermal environmental, dimensional, and flame retardancy characteristics. They possess hydrolytic stability with moldability and colorability.

3-21.2 PROPERTY DATA

Data are presented in Tables 3-100 through 3-102 and Figs. 3-171 through 3-180.

3-22 POLYURETHANE**3-22.1 GENERAL DESCRIPTION**

Glass-reinforced polyurethane is tough and is resistant to wear, abrasion, creep, and exposure to petroleum products.

3-22.2 PROPERTY DATA

Data are presented in Tables 3-103 through 3-105.

3-23 POLYVINYL CHLORIDE (PVC)**3-23.1 GENERAL DESCRIPTION**

Glass-reinforced PVC has excellent fire resistance coupled with good dielectric properties, stiffness, dimensional stability, and resistance to water absorption. The chemical resistance and processibility of PVC-propylene copolymer are superior to the unmodified PVC.

3-23.2 PROPERTY DATA

Data are presented in Tables 3-106 and 3-107.

3-24 STYRENE-ACRYLONITRILE (SAN)**3-24.1 GENERAL DESCRIPTION**

Glass-reinforced styrene-acrylonitrile (SAN) is an exceptionally rigid material with good hardness, strength, and greater chemical resistance than polystyrene compounds. SAN has excellent processability and the lowest mold shrinkage of any thermoplastic available.

3-24.2 PROPERTY DATA

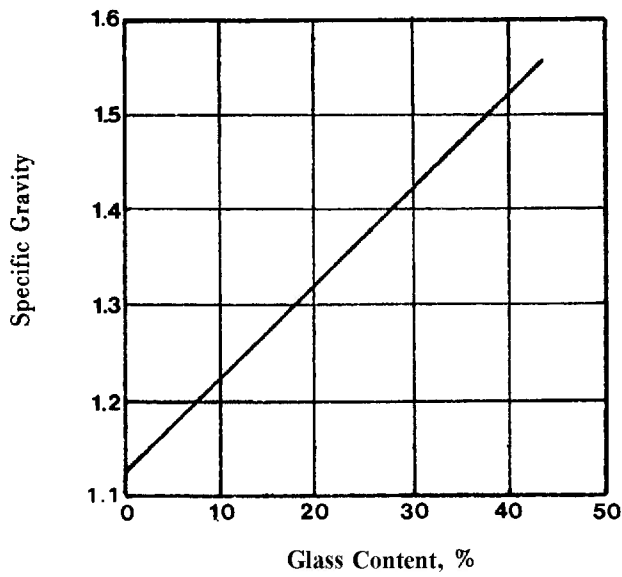
Data are presented in Tables 3-108 through 3-110 and Figs 3-181 through 3-187.

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Figure 3-1. Specific Gravity of Nylon 6 and Nylon 6/6 vs Glass Content³

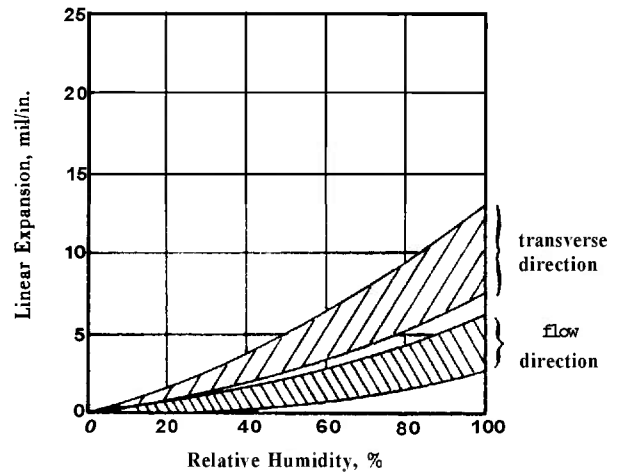
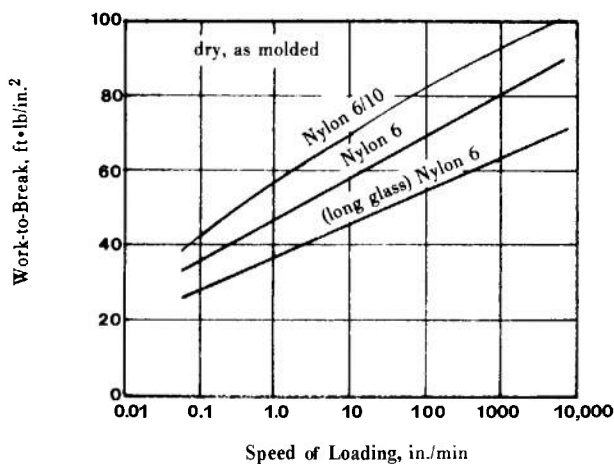
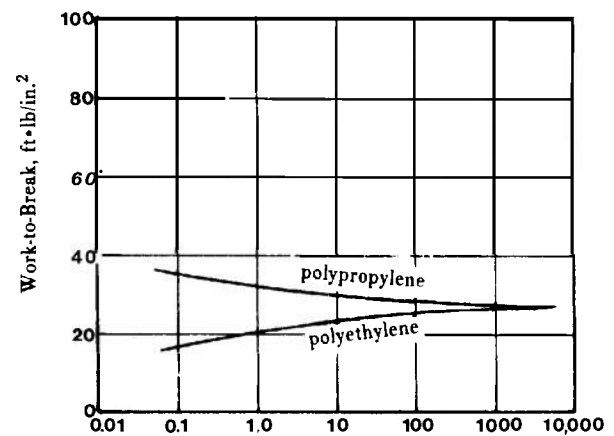


Figure 3-2. Effect of Humidity on Dimensions at Equilibrium, Zytel 70 G-33 (Ref. 4)



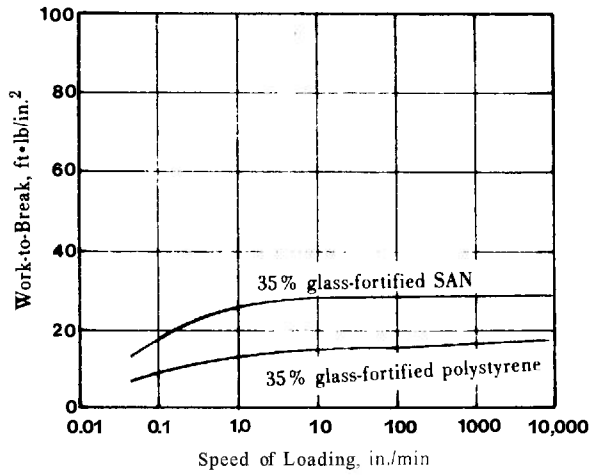
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Figure 3-3. Work-to-Break vs Loading Speed for 30% Glass-Reinforced Nylon 6/10 and Nylon 6 (Ref. 1)



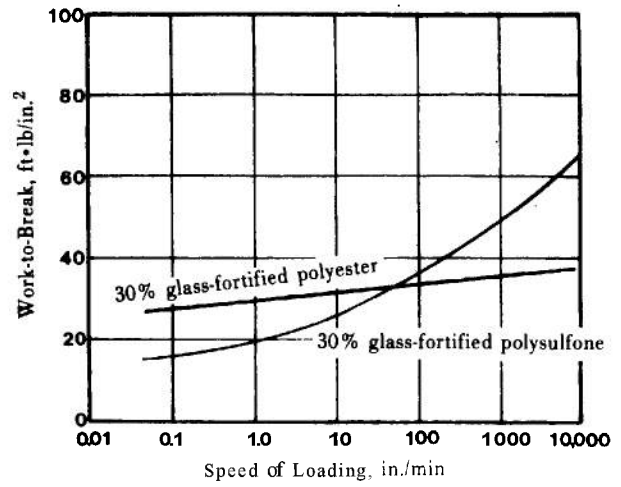
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Figure 3-4. Work-to-Break vs Loading Speed for 30% Glass-Reinforced Polypropylene and Polyethylene'



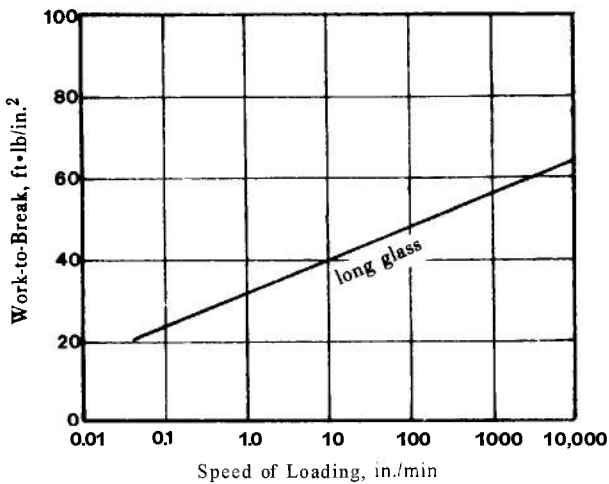
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Figure 3-5. Work-to-Break vs Loading Speed for 35% Glass-Reinforced SAN and Polystyrene'



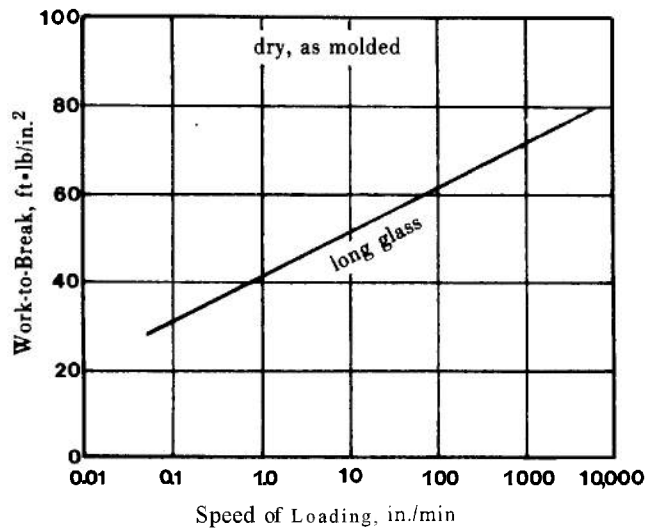
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Figure 3-6. Work-to-Break vs Loading Speed for 30% Glass-Reinforced Polyester and Polysulfone'



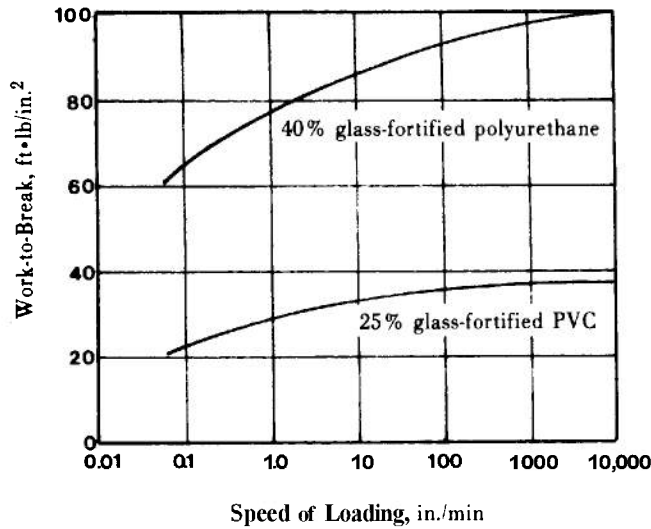
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Figure 3-7. Work-to-Break as a Function of Loading Speed for 40% Glass-Reinforced Polycarbonate'



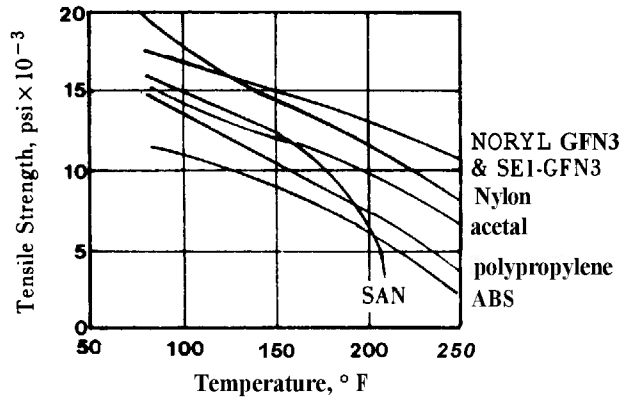
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Figure 3-8. Work-to-Break as a Function of Loading Speed for 30% Glass-Reinforced Nylon 6/6 (Ref. 1)



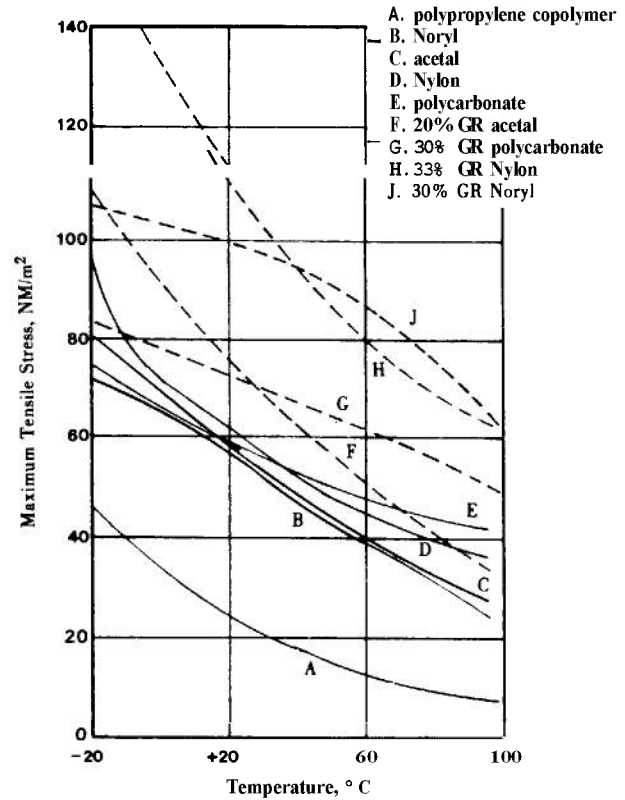
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Figure 3-9. Work-to-Break vs Loading Speed for Glass-Reinforced PVC and Polyurethane'



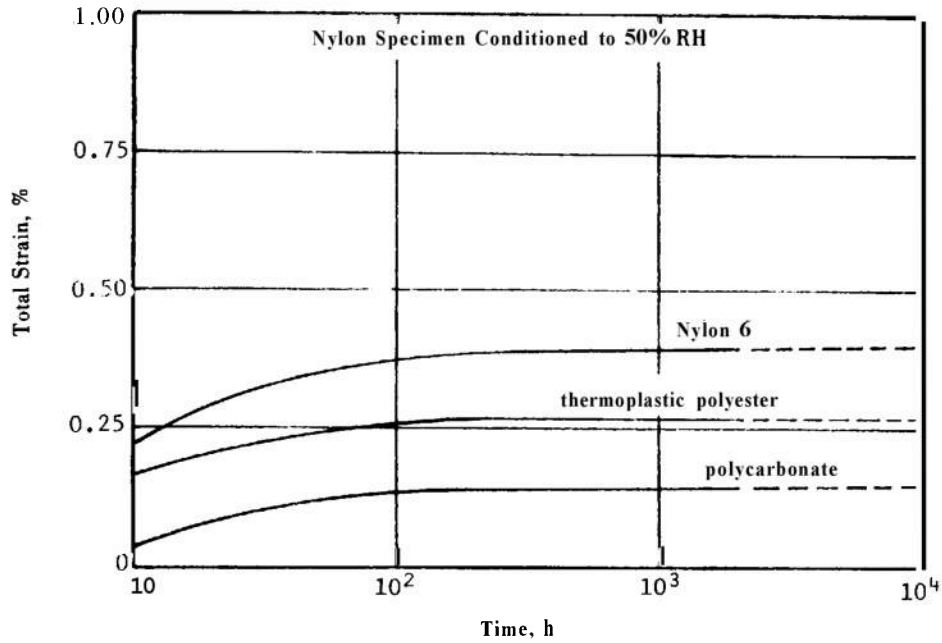
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Figure 3-10. Tensile Strength vs Temperature of 30% Glass-Reinforced Thermoplastics'



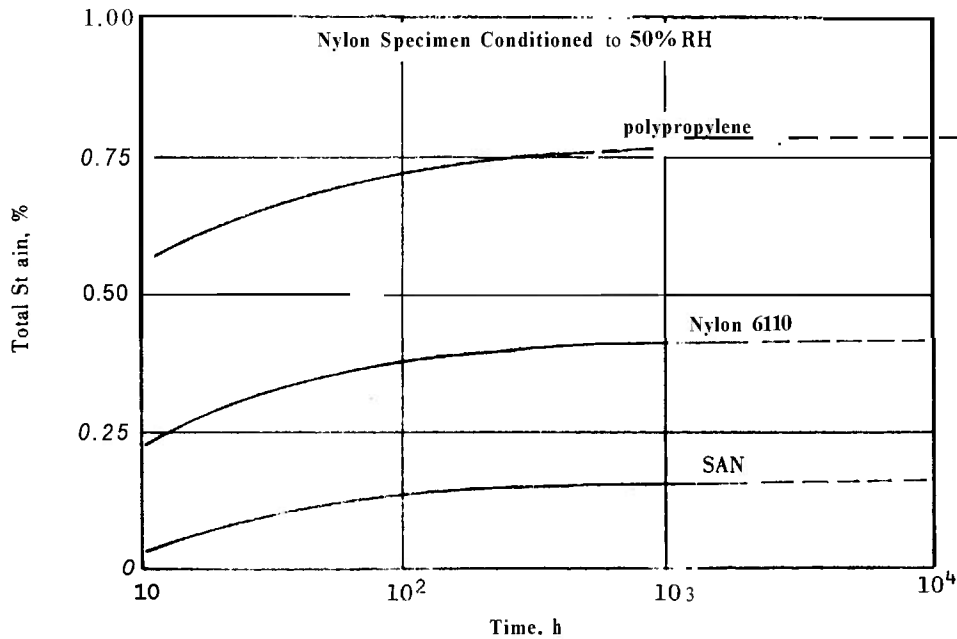
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Figure 3-11. Maximum Tensile Stress vs Temperature⁶



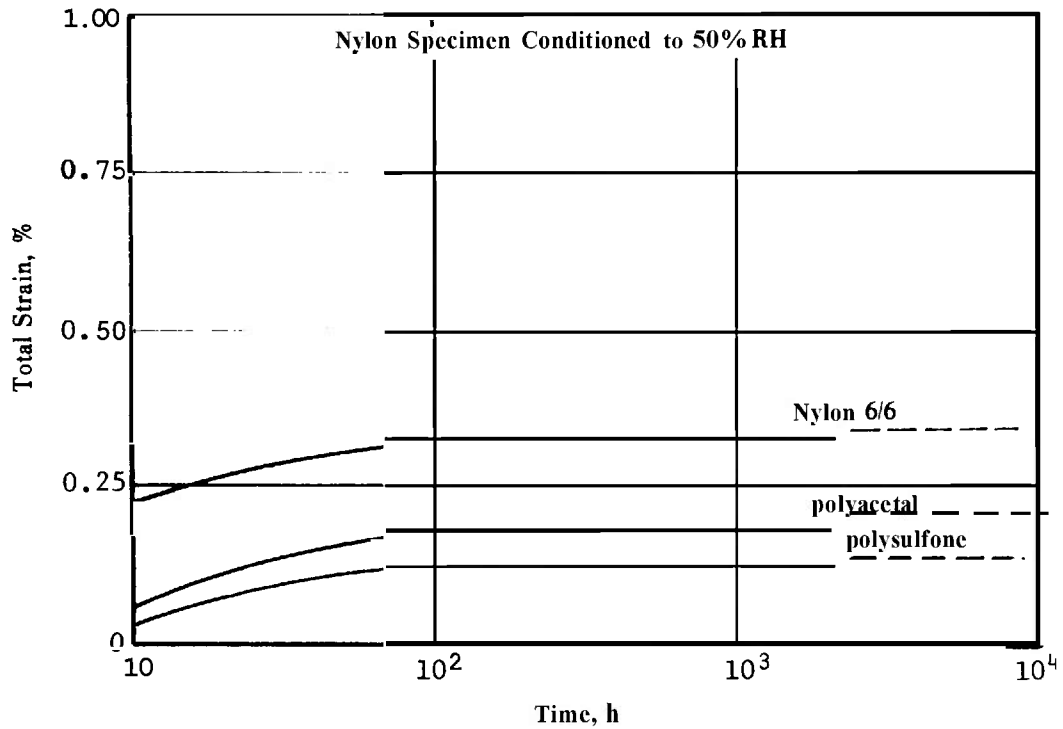
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Figure 3-12. Flexural Creep of 15% TFE, 30% Glass-Reinforced Polycarbonate, Nylon 6, and Thermoplastic Polyester Resins at 73°F, 2000 psi in Air⁷



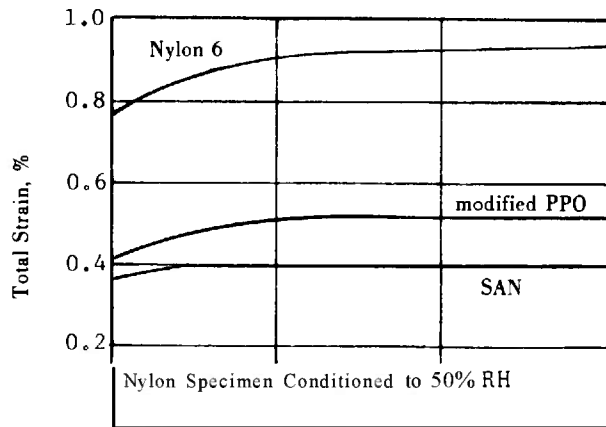
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Figure 3-13. Flexural Creep of 15% TFE, 30% Glass-Reinforced Polypropylene, SAN, Nylon 6/10 Resins at 73°F, 2000 psi in Air⁷



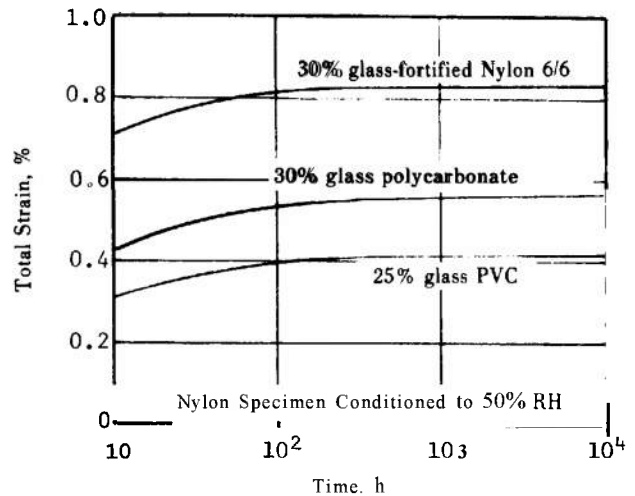
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Figure 3-14. Flexural Creep of 15% TFE, 30% Glass-Reinforced Polyacetal, and Nylon 6/6 Resins at 73°F, 2000 psi in Air⁷



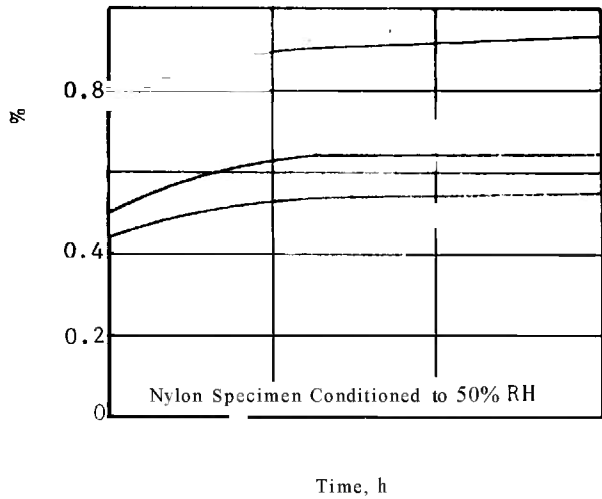
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Figure 3-15. Flexural Creep of 30% Glass-Reinforced, Flame Retardant Nylon 6, SAN, and Modified PPO at 73°F and 5000 psi (Ref. 2)



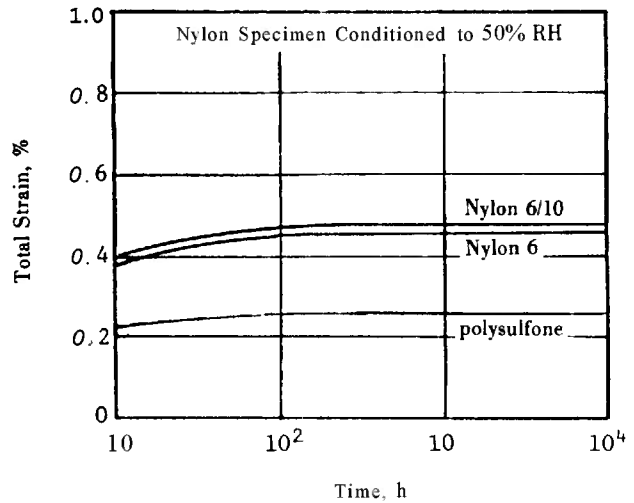
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Figure 3-16. Flexural Creep of Glass-Reinforced PVC, Polycarbonate, and Flame Retardant Nylon 6/6 at 73°F, 5000 psi (Ref. 2)



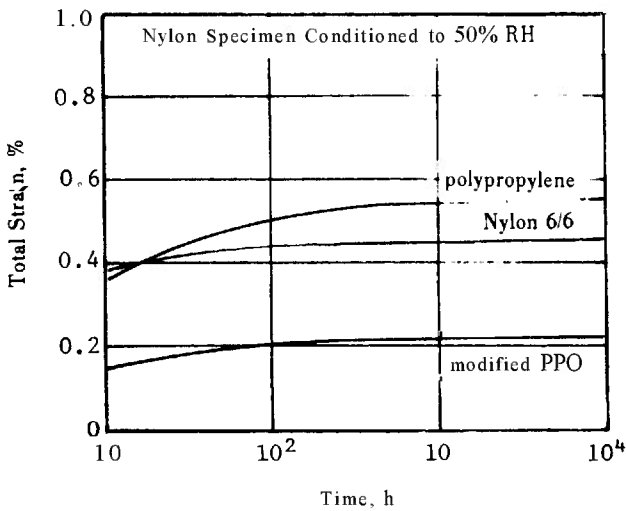
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Figure 3-17. Flexural Creep of 30% Glass-Reinforced, Flame Retardant Nylon 6/10 and Polysulfone at 73°F, 5000 psi (Ref. 2)



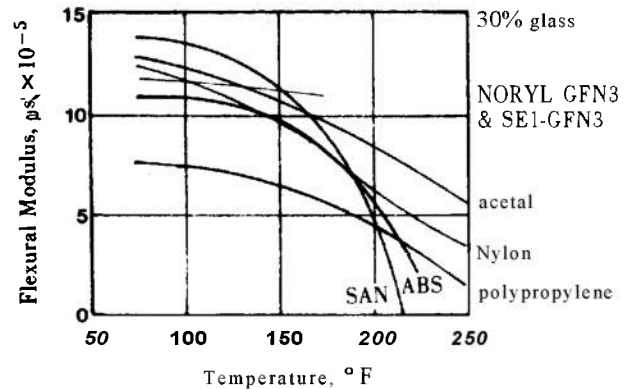
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Figure 3-18. Flexural Creep of 30% Glass-Reinforced, Flame Retardant Nylon 6, Nylon 6/10, and Polysulfone at 73°F, 2500 psi (Ref. 2)



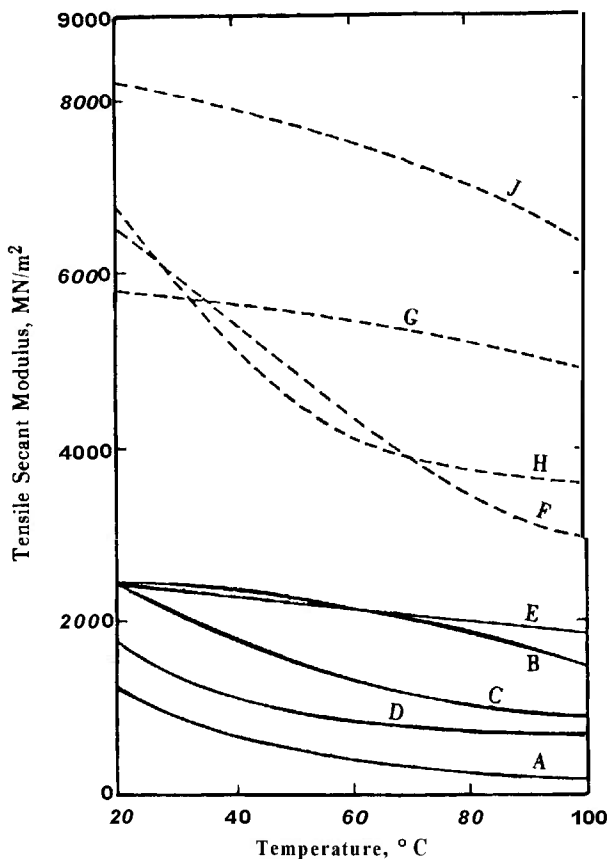
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Figure 3-19. Flexural Creep of 30% Glass-Reinforced, Flame Retardant Nylon 6/6, Polypropylene, and Modified PPO at 73°F, 2500 psi (Ref. 2)



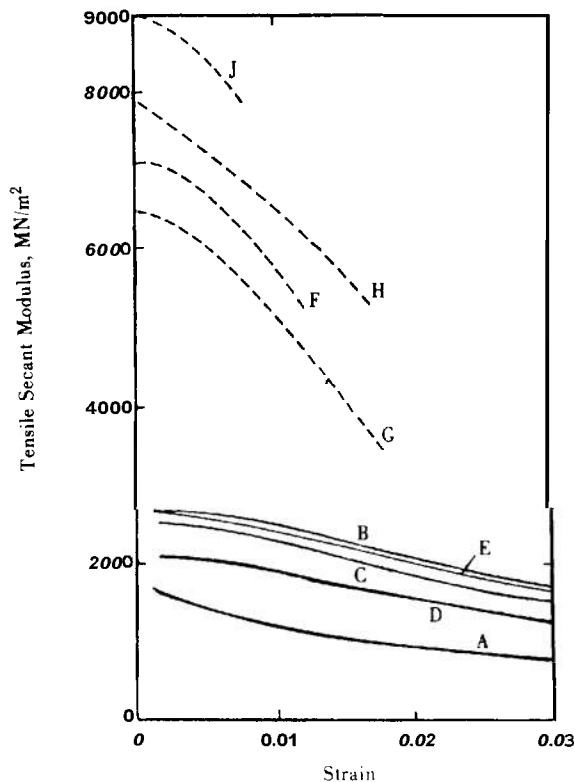
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Figure 3-20. Flexural Modulus vs Temperature of 30% Glass-Reinforced Thermoplastics'



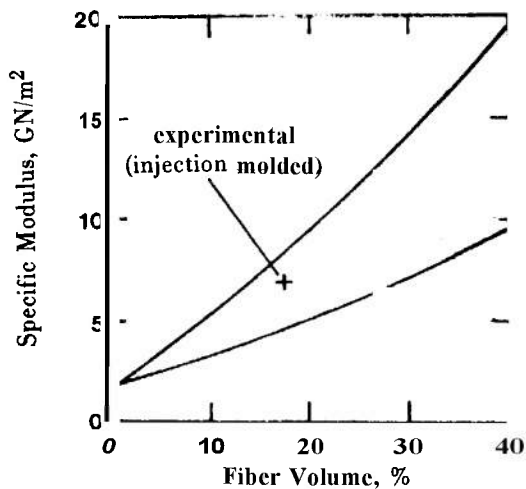
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Figure 3-21. 100-s 0.5% Tensile Secant Modulus vs Temperature (Designations as in Fig. 3-11)⁶



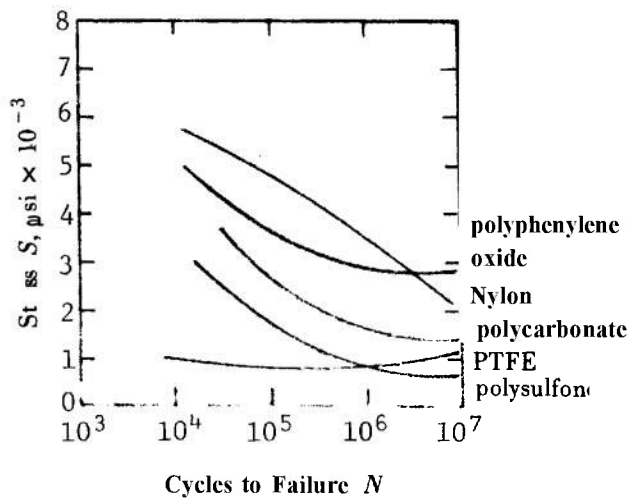
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Figure 3-22. 100-s 0.5% Tensile Secant Modulus vs Strain (Designations as in Fig. 3-11)⁶



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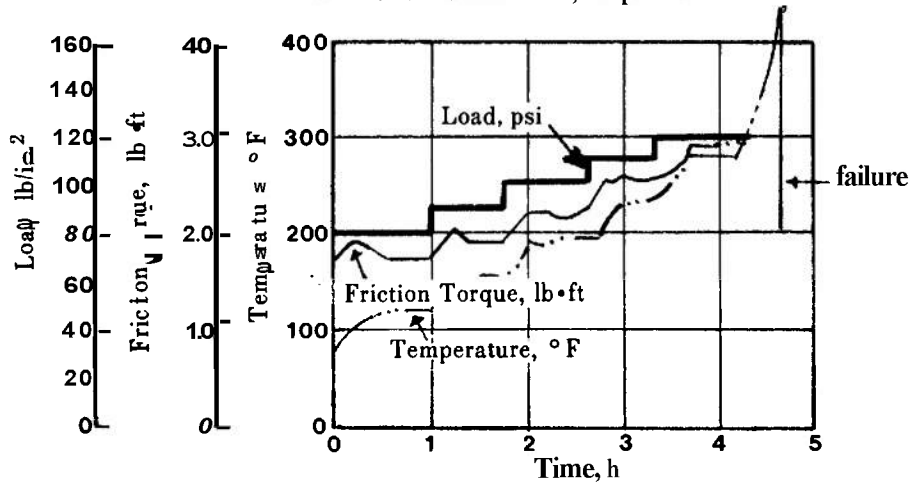
Figure 3-23. Predicted Specific Modulus of 0.15-mm Glass Fibers in Nylon 6/6 (Ref. 6)



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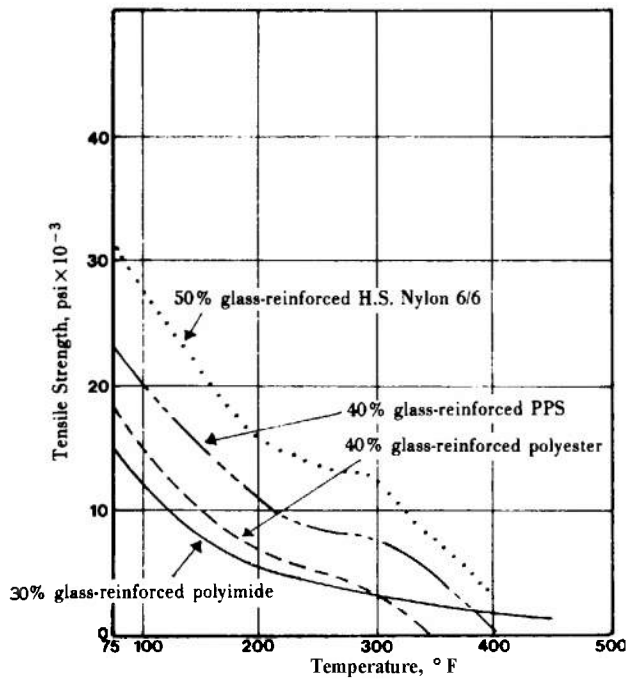
Figure 3-24. Fatigue Life of Several Compounds, Tested at a Frequency of 1800 Cycles per Min⁷

BRG MATERIAL: typical 1 in. x 1 in.
 SHAFT: cold rolled carbon steel
 FINISH: 16 microinches (RMS)
 HARDNESS: 18-22R
 SURFACE VELOCITY: 100 ft/min
 "PV" LIMIT: 100 ft/min = 12,000 psi·ft/min



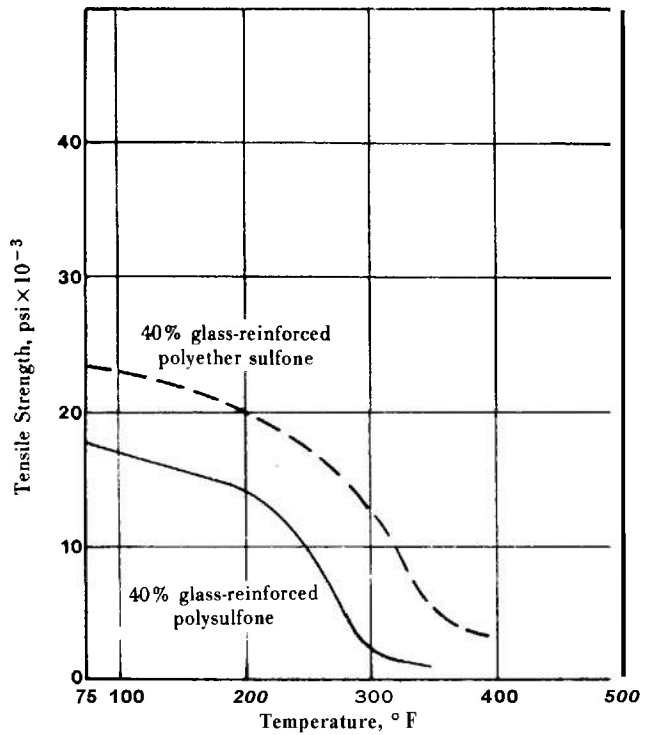
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Figure 3-25. Load Stepping Test⁷



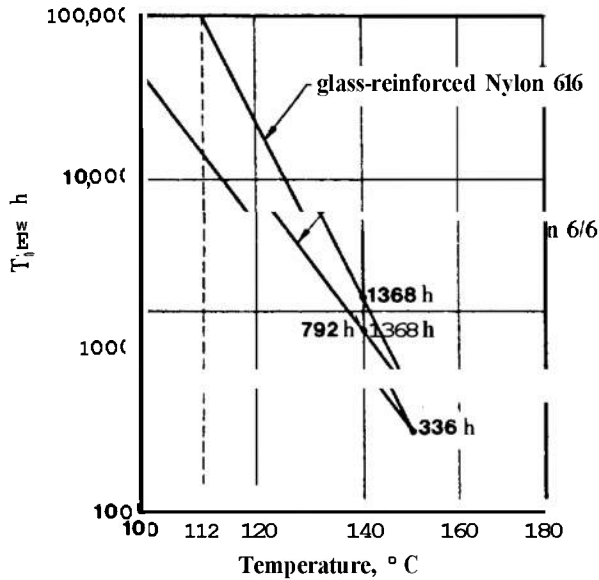
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Figure 3-26. Tensile Strength vs Temperature of Crystalline Composites⁷



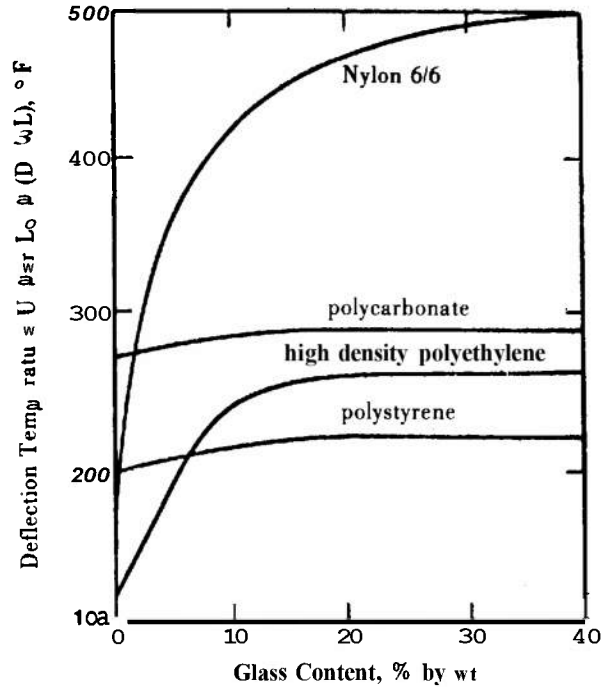
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Figure 3-27. Tensile Strength vs Temperature of Amorphous Composites⁷



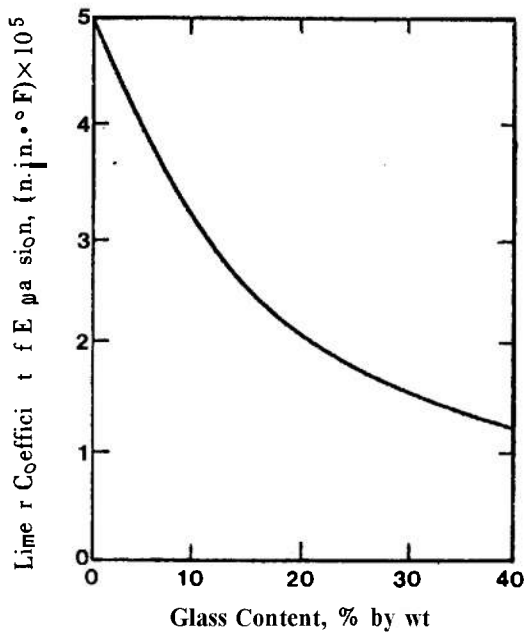
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Figure 3-28. Time – Temperature Relationships for Tensile Impact Strength of Heat-Stabilized Reinforced (30% Glass) and Unreinforced Nylon 6/6 (Ref. 2)



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Figure 3-29. Effect of Glass Fiber Content on Deflection Temperature Under Load (DTUL) for Two Amorphous Polymers (Polycarbonate and Polystyrene) and Two Crystalline Polymers (High-Density Polyethylene and Nylon 6/6 (Typically, the optimum effect is reached at 20% glass fiber content, with the exception of nylons where 30% is the optimum.)



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Figure 3-30. Dimensional Stability (Coefficient of Expansion) of ABS as a Function of Glass Fiber Reinforcement (Dimensional stability improves substantially with the addition of up to about 30% of glass fiber.)

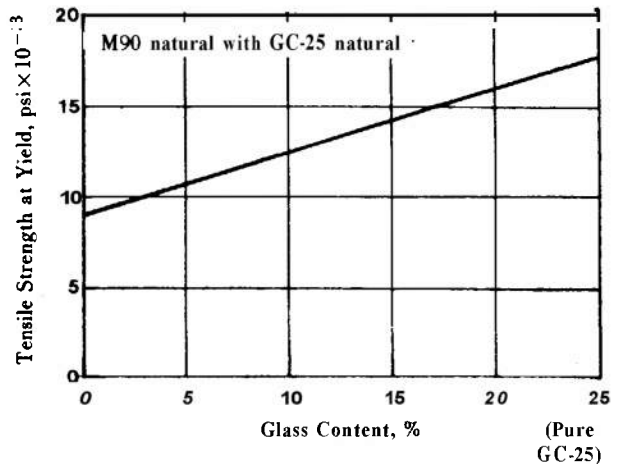


Figure 3-31. Tensile Strength as a Function of Glass Content for Celcon Blends¹⁵

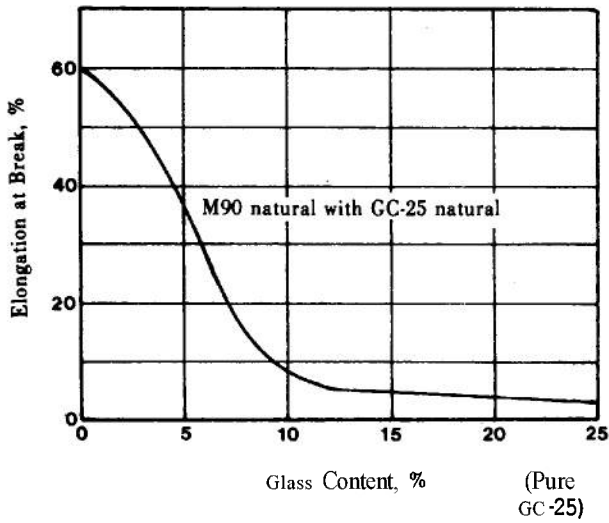


Figure 3-32. Tensile Elongation at Break as a Function of Glass Content for Celcon Blends¹⁵.

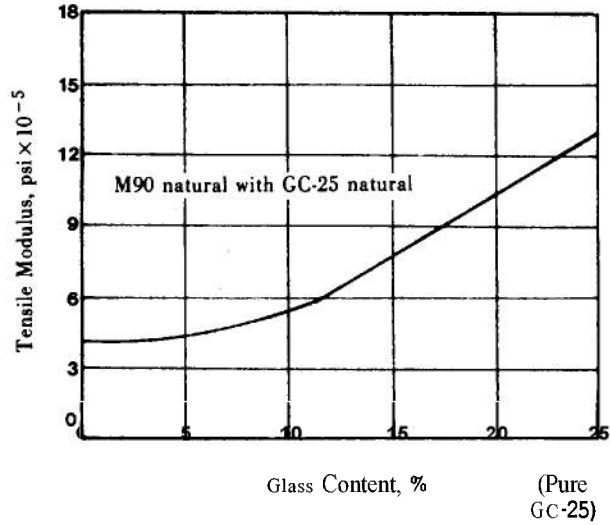


Figure 3-33. Tensile Modulus as a Function of Glass Content for Celcon Blends¹⁵.

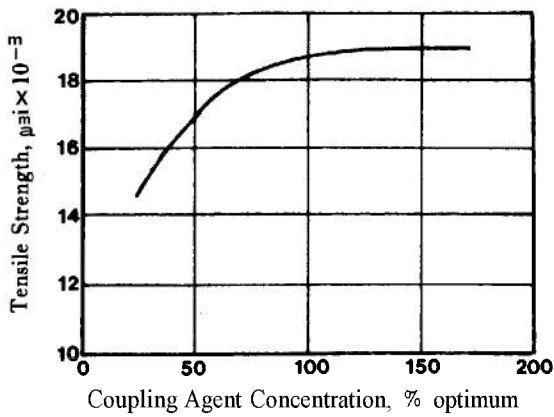


Figure 3-34. Tensile Strength vs Coupling Agent Concentration¹⁶.

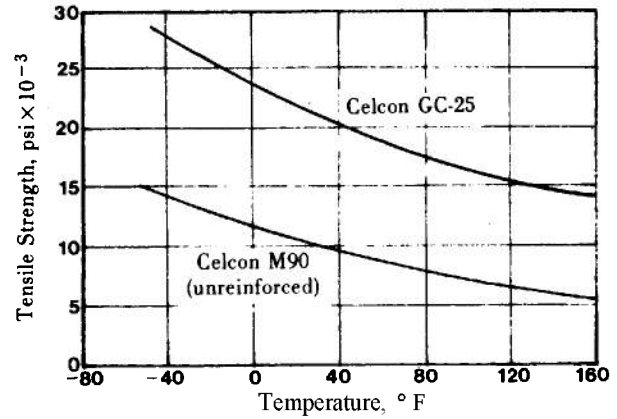


Figure 3-35. Tensile Strength vs Temperature¹⁶.

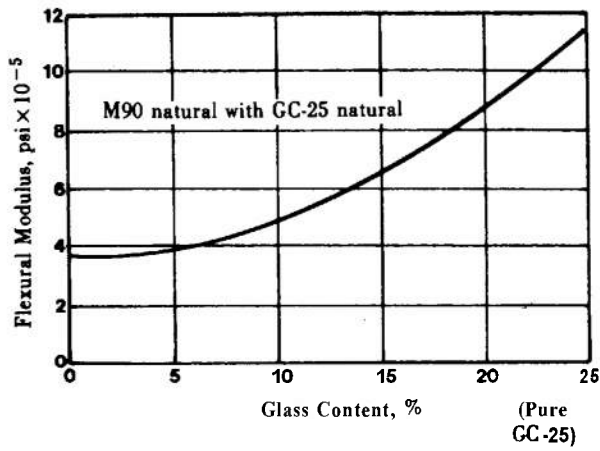


Figure 3-36. Flexural Modulus as a Function of Glass Content for Celcon Blends¹⁵

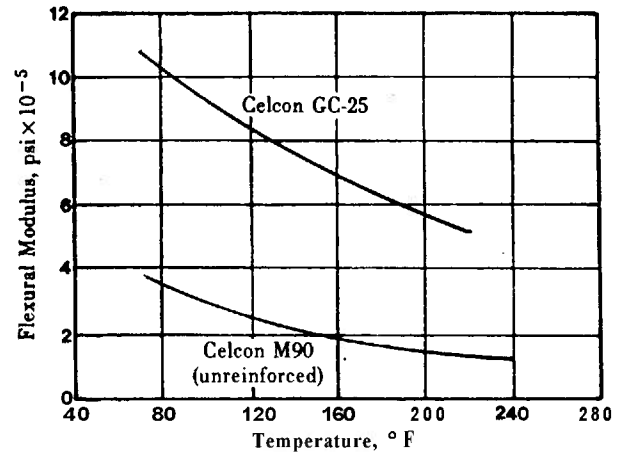


Figure 3-37. Flexural Modulus vs Temperature¹⁵

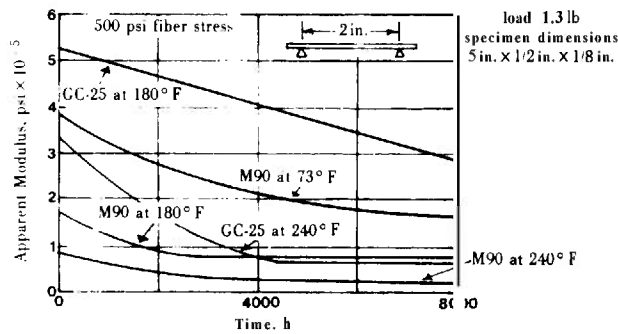


Figure 3-38. Apparent Modulus vs Time¹⁵

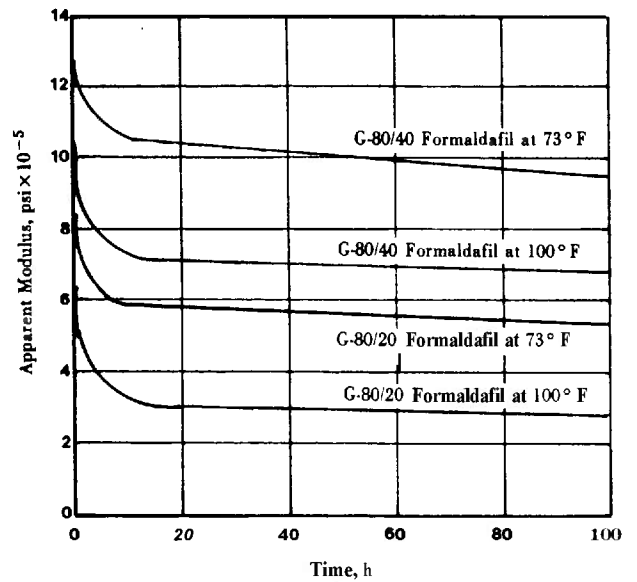


Figure 3-39. Creep—Apparent Modulus vs Time¹⁷

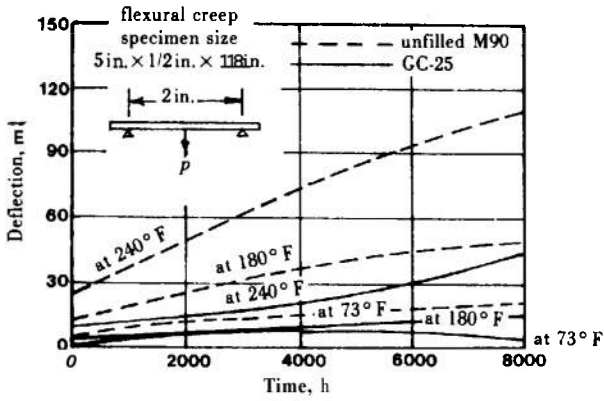


Figure 3-40. Flexural Creep of GC 25 (Ref. 15)

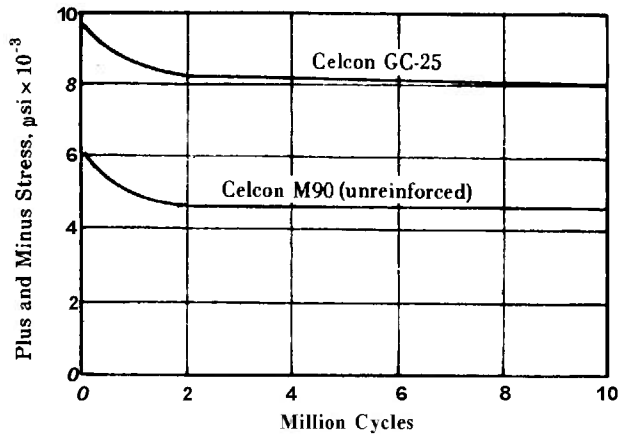


Figure 3-41. Flexural Fatigue Curve for Various Compositions of Celcon¹⁵

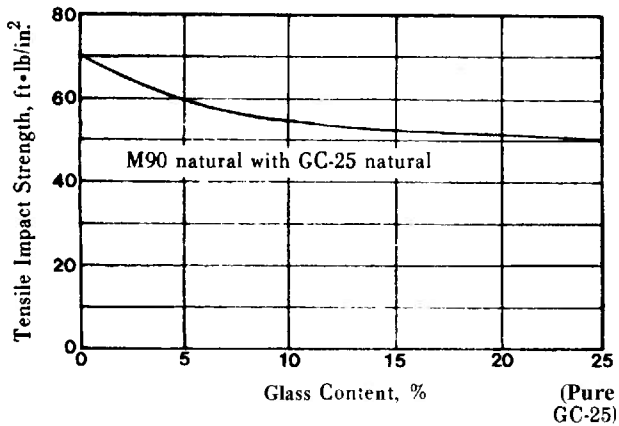


Figure 3-42. Tensile Impact Strength as a Function of Glass Content for Celcon Blends¹⁵

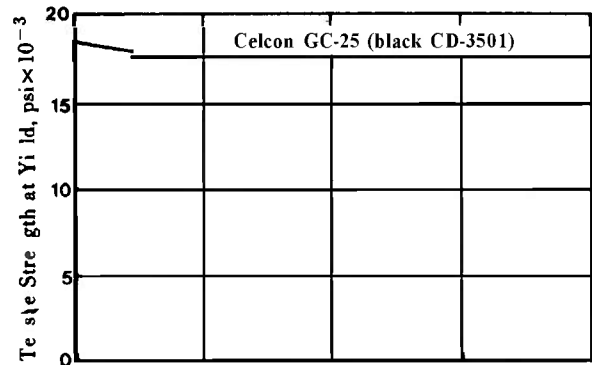


Figure 3-43. Effect of Outdoor Exposure (Clark, NJ) on Tensile Strength¹⁵

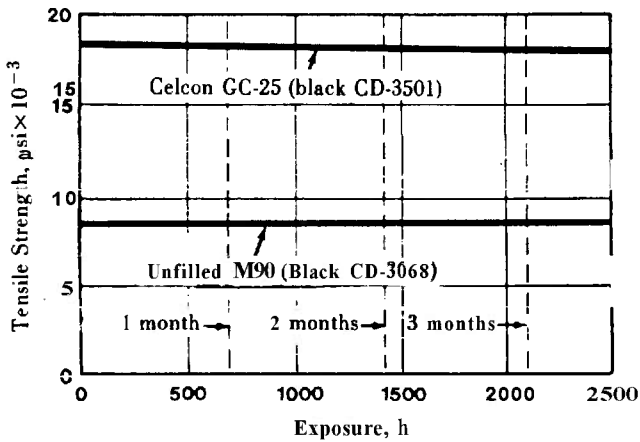


Figure 3-44. Tensile Strength vs Exposure of Celcon in Atlas XW Weatherometer¹⁵

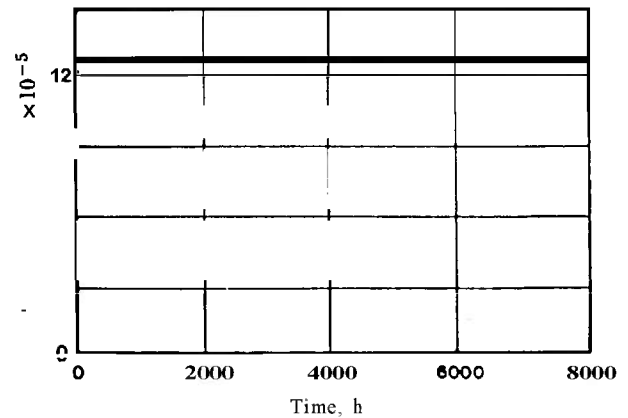


Figure 3-45. Effect of Outdoor Exposure (Clark, NJ) on Tensile Modulus¹⁵

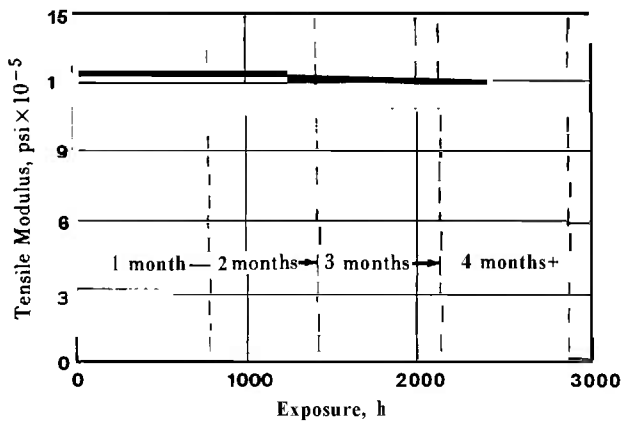


Figure 3-46. Tensile Modulus vs Exposure in Atlas XW Weatherometer¹⁵

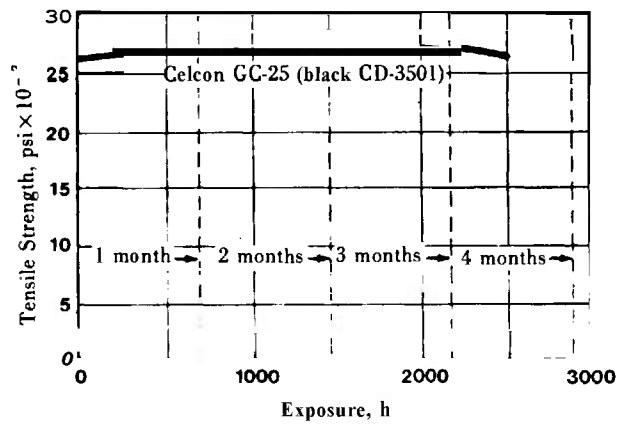


Figure 3-47. Flexural Strength vs Exposure in Atlas XW Weatherometer¹⁵

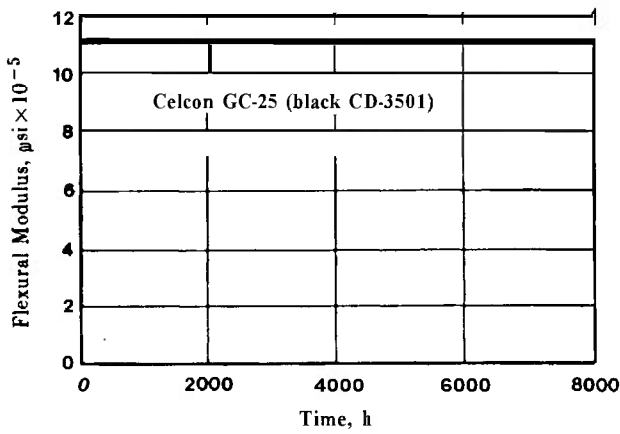


Figure 3-48. Effect of Outdoor Exposure (Clark, NJ) on Flexural Modulus¹⁵

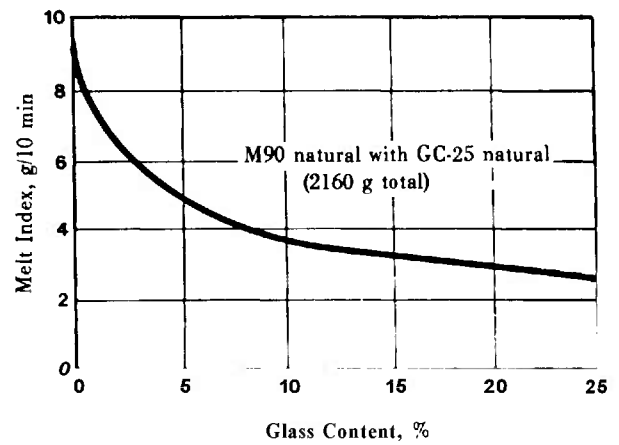


Figure 3-49. Melt Index as a Function of Glass Content for Celcon Blends¹⁵

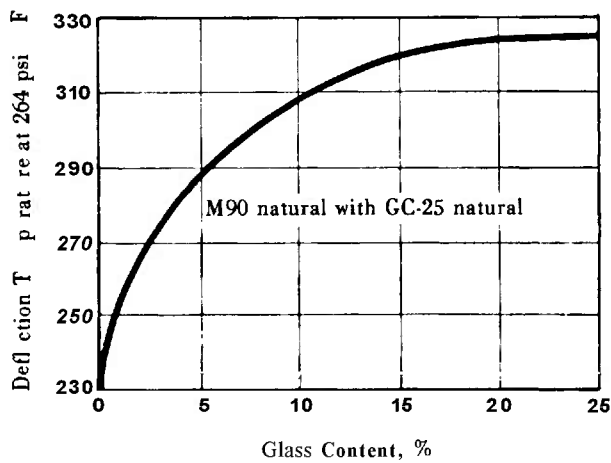


Figure 3-50. Deflection Temperature as a Function of Glass Content for Celcon Blends¹⁵

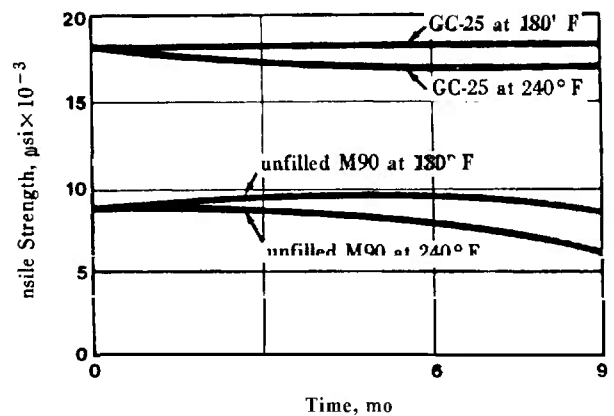


Figure 3-51. Effect of Heat Aging on GC 25 Tensile Strength¹⁵

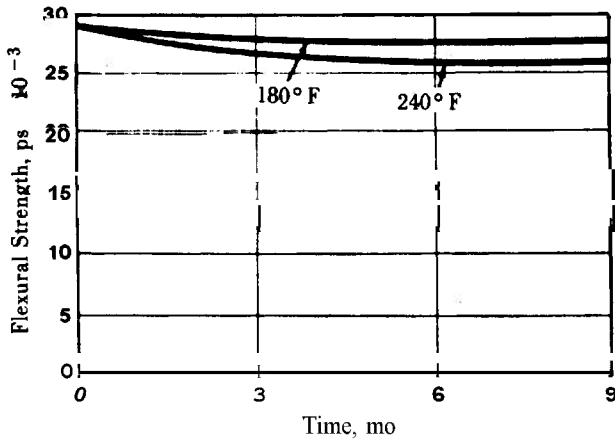


Figure 3-52. Effect of Heat Aging on GC 25 Flexural Strength¹⁵

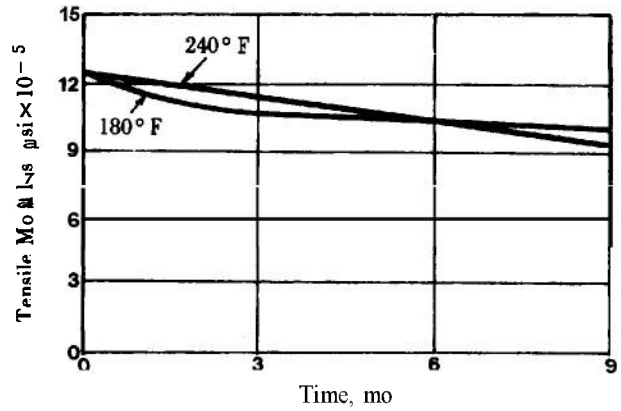


Figure 3-53. Effect of Heat Aging on GC 25 Tensile Modulus¹⁵

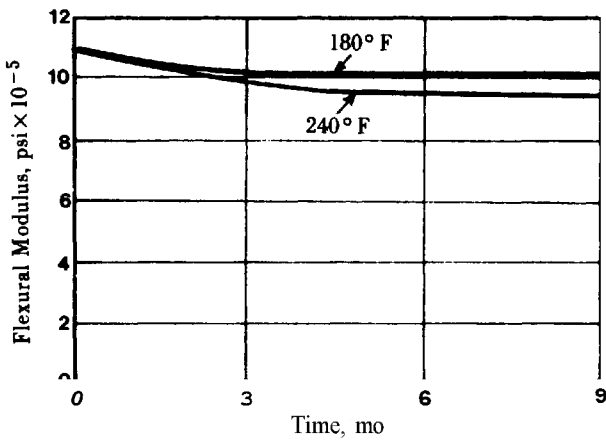


Figure 3-54. Effect of Heat Aging on Flexural Modulus

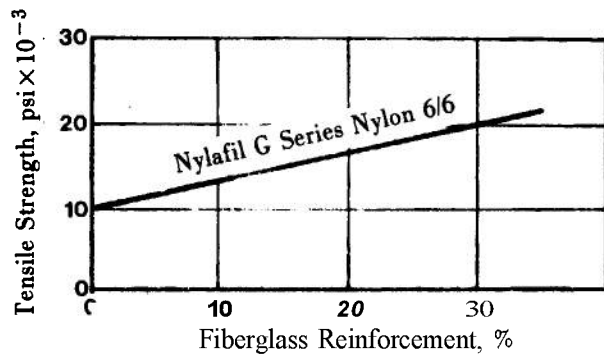


Figure 3-55. Tensile Strength vs Percent Fiberglass Reinforcement, Nylon 6/6 (Ref. 22)

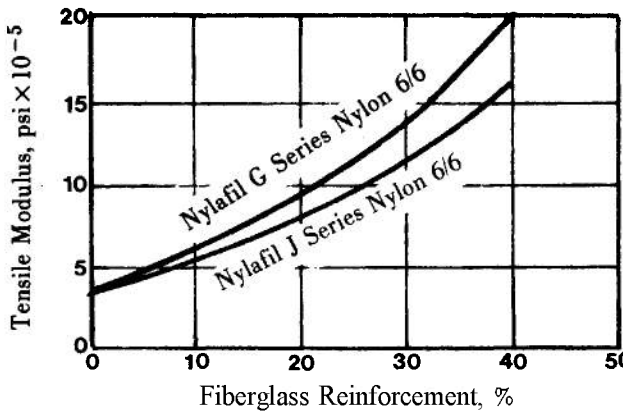


Figure 3-56. Tensile Modulus vs Percent Fiberglass Reinforcement, Nylon 6/6 (Ref. 22)

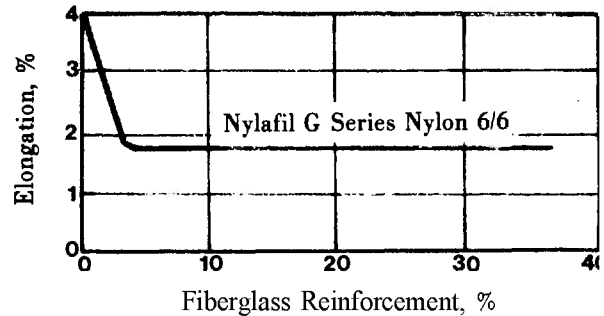
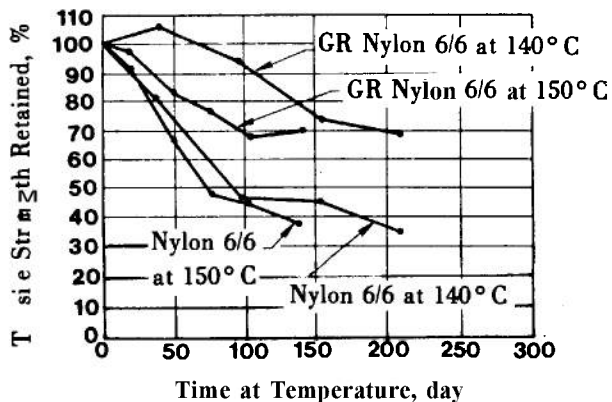
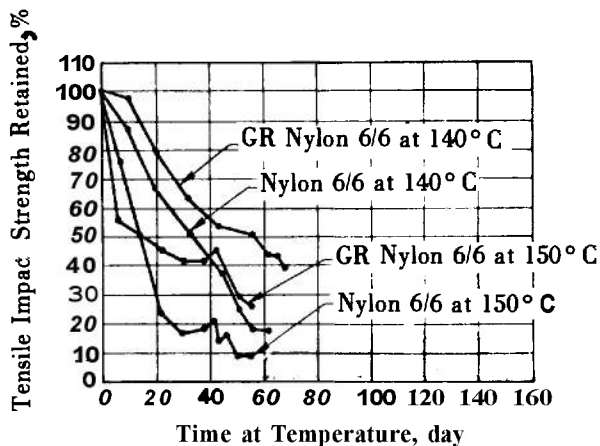


Figure 3-57. Tensile Elongation vs Percent Fiberglass Reinforcement, Nylon 6/6 (Ref. 22)



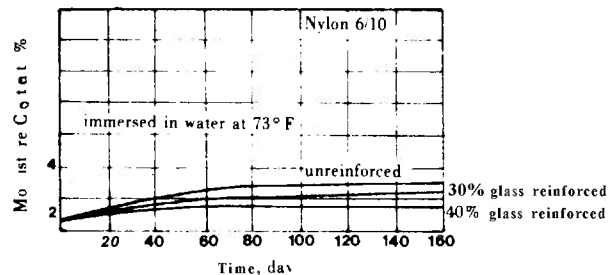
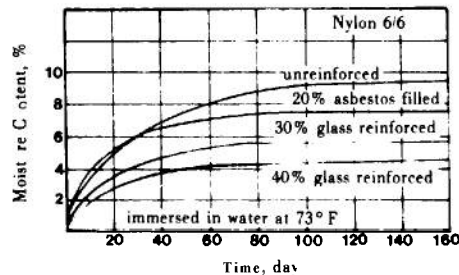
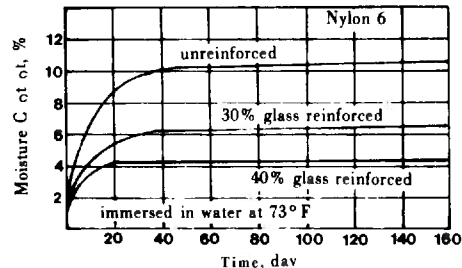
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Figure 3-58. Tensile Strength vs Time at 140° and 150°C, Nylon 6/6 (Ref. 23)



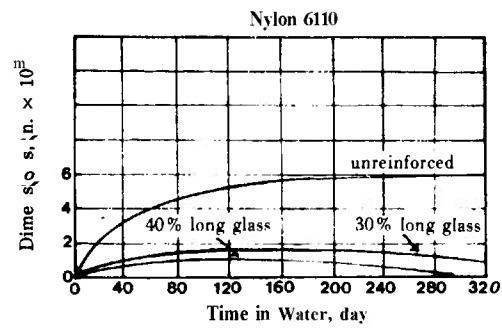
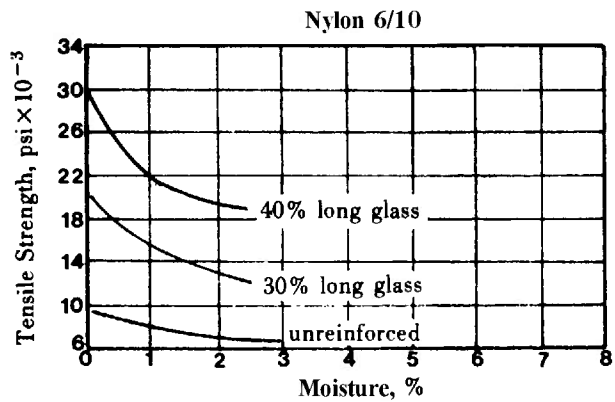
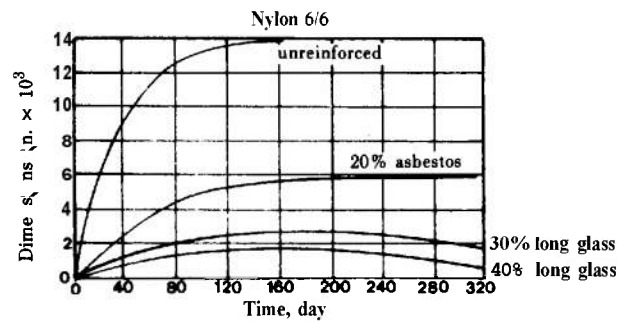
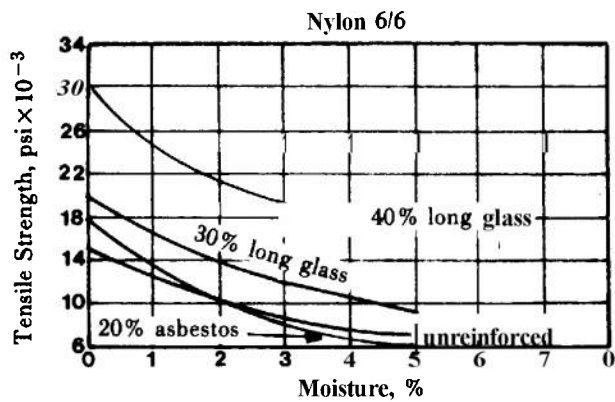
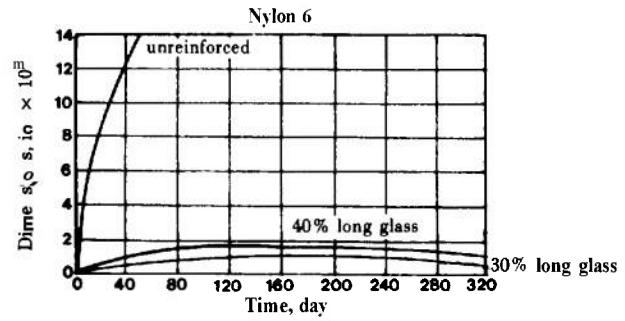
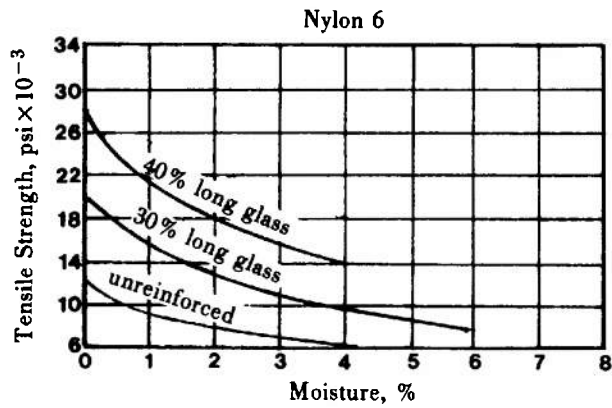
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Figure 3-59. Tensile Impact Strength vs Time at 140° and 150°C, Nylon 6/6 (Ref. 23)



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Figure 3-60. Moisture Content vs Time for Nylons 6, 6/6, and 6/10 (Ref. 24)

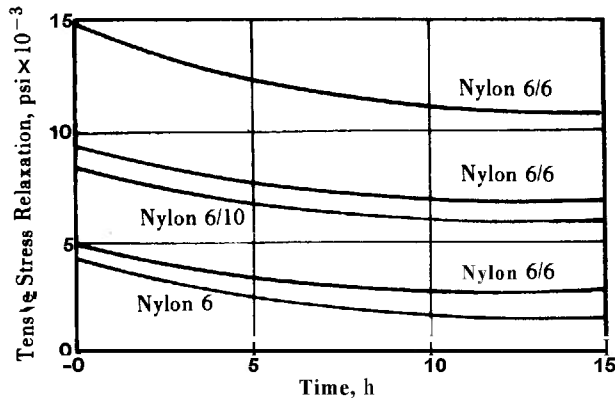


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Figure 3-61. Moisture Content vs Tensile Strength for Nylons 6, 6/6, and 6/10 (Ref. 24)

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Figure 3-62. Dimensions vs Time in Water for Nylons 6, 6/6, and 6/10 (Ref. 24)



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Figure 3-63. Tensile Stress Relaxation 40% Glass-Reinforced Nylons 6, 6/6, and 6/10 (Ref. 25)

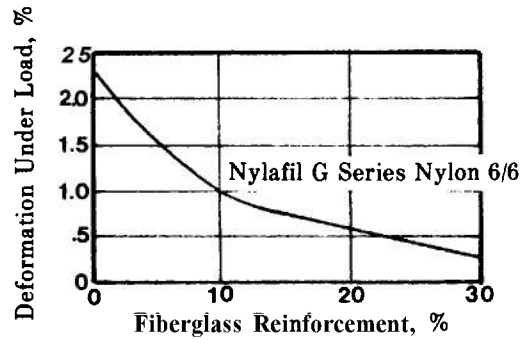
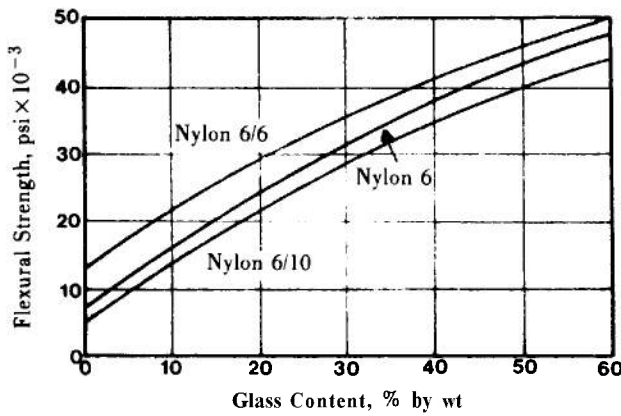
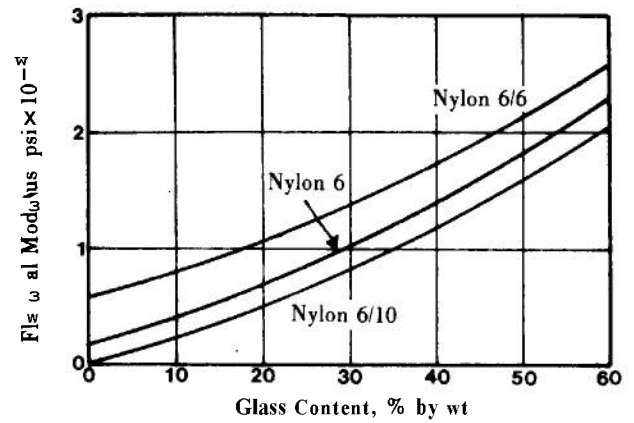


Figure 3-64. Deformation Under Load vs Percent Fiberglass for Nylon 6/6 (Ref. 22)



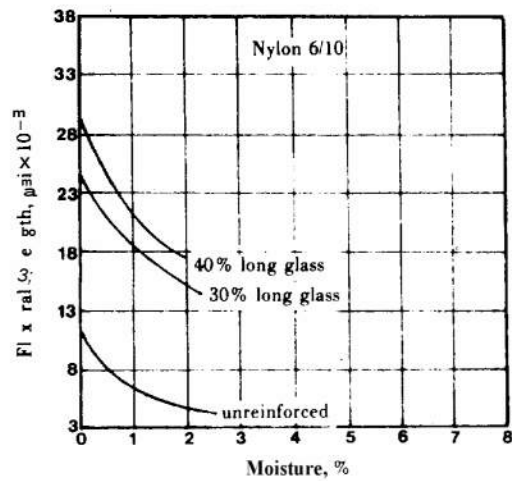
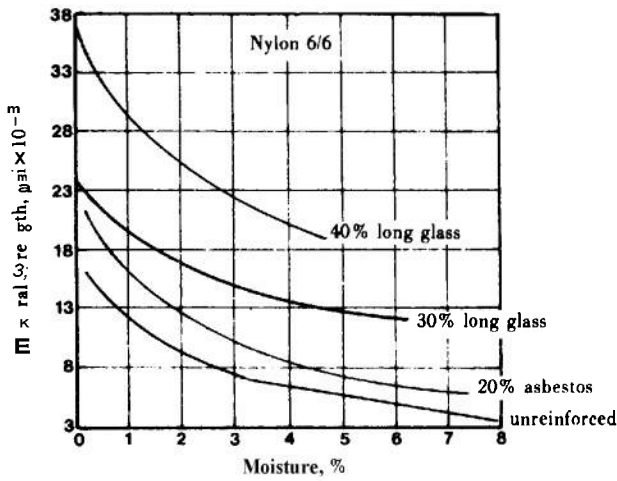
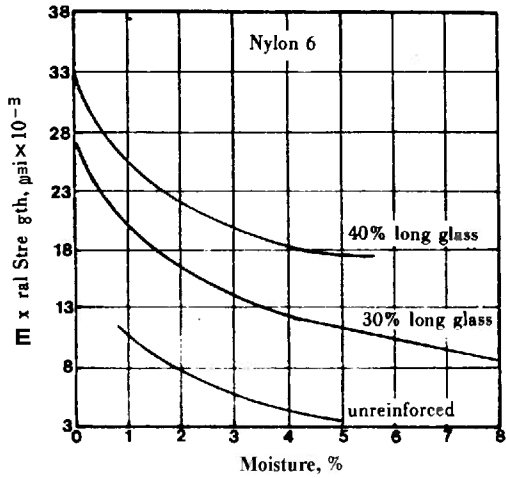
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Figure 3-65. Flexural Strength vs Glass Content for Nylons 6, 6/6, and 6/10 (Ref. 25)



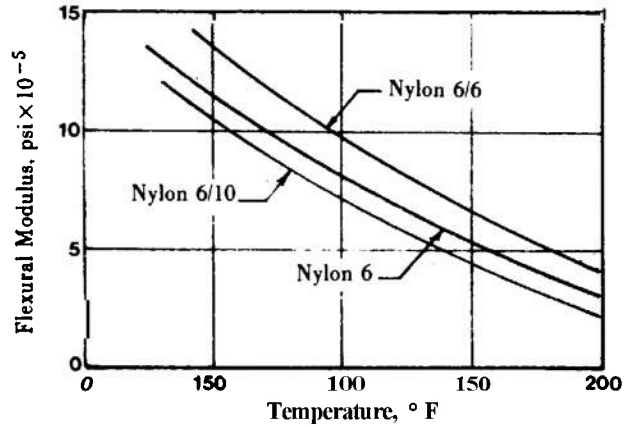
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Figure 3-66. Flexural Modulus vs Glass Content for Nylons 6, 6/6, and 6/10 (Ref. 25)



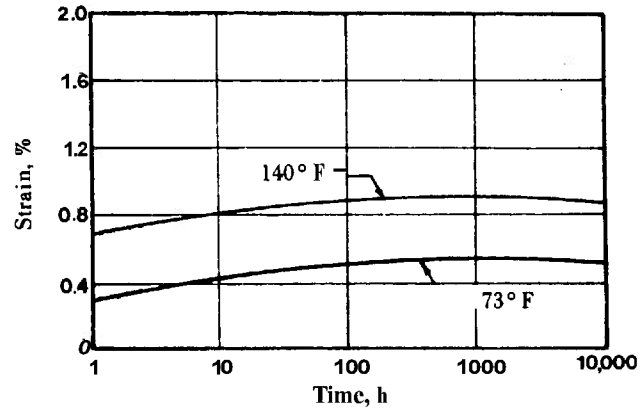
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Figure 3-67. Flexural Strength vs Moisture for Nylons 6, 6/6, and 6/10 (Ref.24)



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Figure 3-68. Flexural Modulus vs Temperature for 30% Glass-Reinforced Nylons 6, 6/6, and 6/10 (Ref. 25)



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Figure 3-69. Flexural Creep at 5000 psi, 73° F and 140° F for 40% Glass-Reinforced Nylon 6/6 Resin²⁵

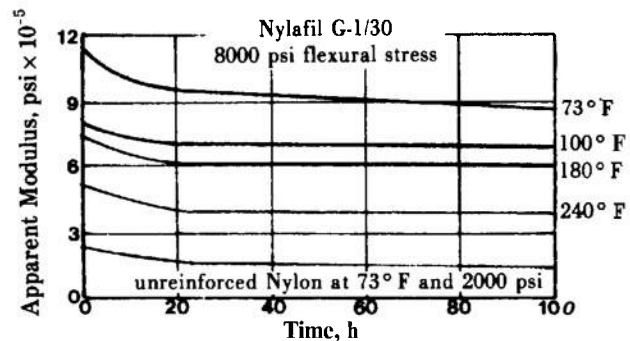


Figure 3-70. Flexural Creep—Apparent Modulus vs Time for Nylon 6/6, 30% Glass Reinforced¹¹

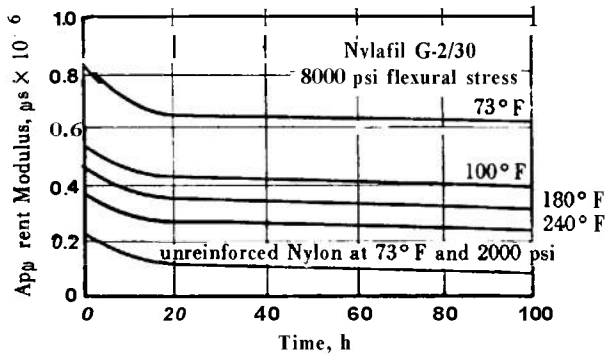


Figure 3-71. Flexural Creep—Apparent Modulus vs Time for Nylon 6/10, 30% Glass Reinforcedⁿ

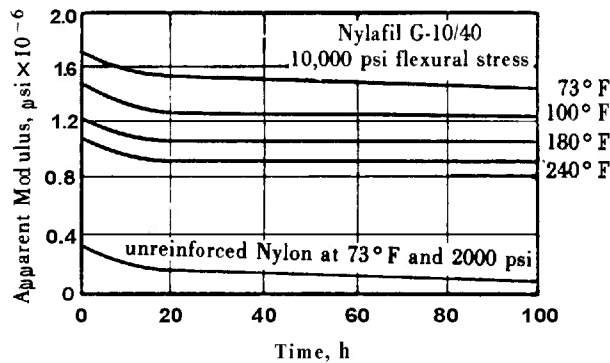
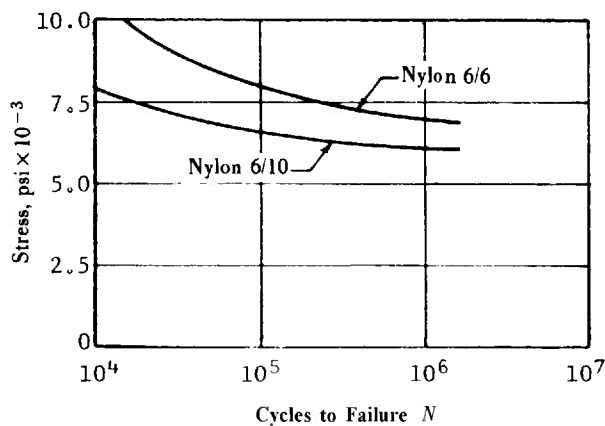
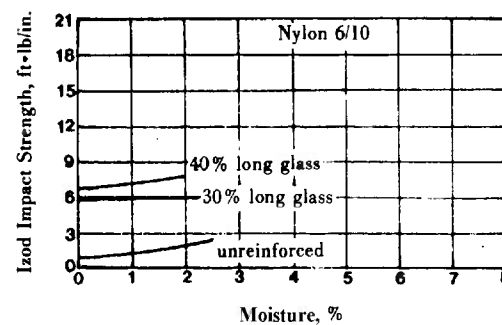
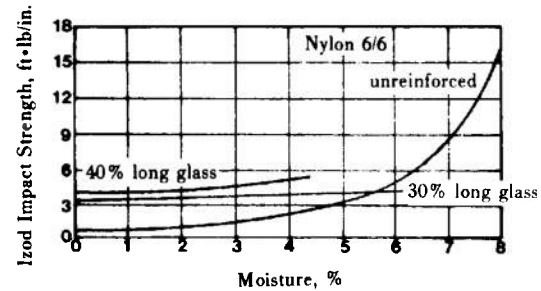
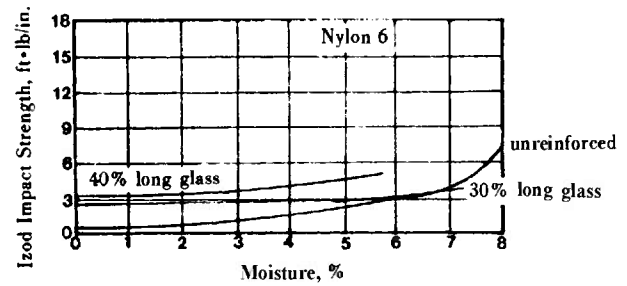


Figure 3-72. Flexural Creep—Apparent Modulus vs Time for Nylon 6/6, 40% Glass Reinforcedⁿ



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Figure 3-73. Fatigue Endurance for 40% Glass-Reinforced Nylons 6/6 and 6/10 (Ref. 25)



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Figure 3-74. Izod Impact Strengths vs Moisture for Nylons 6, 6/6, and 6/10 (Ref. 24)

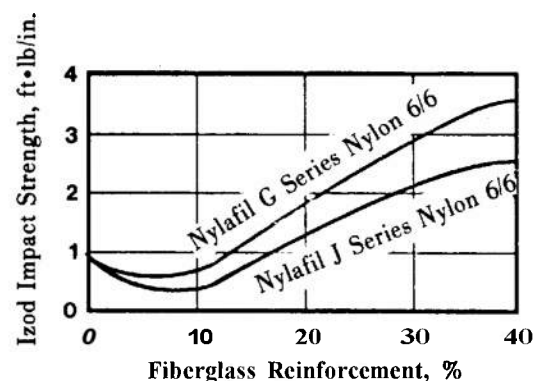
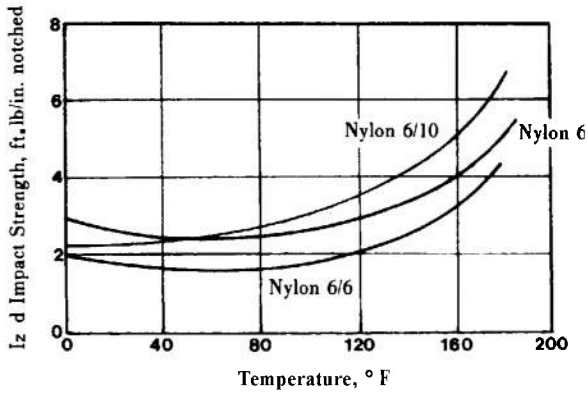


Figure 3-75. Izod Impact Strength vs Fiberglass Reinforcement for Nylon 6/6 (Ref. 22)



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Figure 3-76. Notched Izod Impact Strength vs Temperature for 30% Glass-Reinforced Nylons 6, 6/6, and 6/10 (Ref. 25)

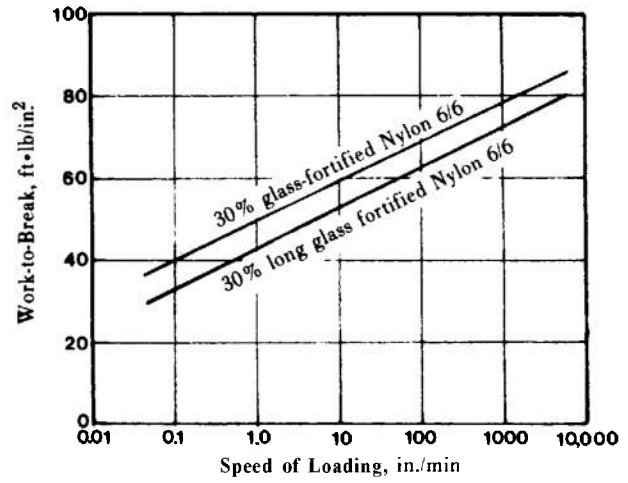


Figure 3-77. Work-to-Break as a Function of Loading Speed for Glass-Reinforced Nylon 6/6 Resins'

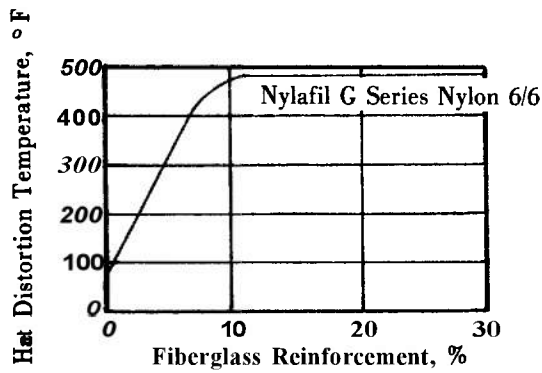


Figure 3-78. Deflection Temperature Under Load vs Percent Fiberglass, Nylon 6/6 (Ref. 22)

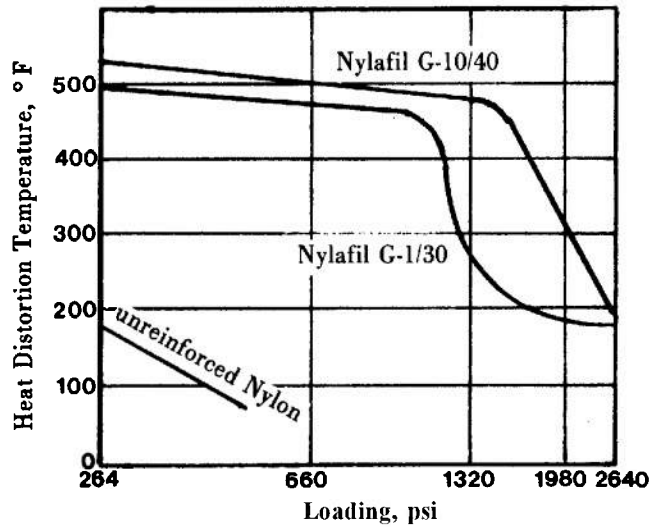


Figure 3-79. Deflection Temperature vs Loading for 30% and 40% Glass-Reinforced Nylon 6/6 (Ref. 22)

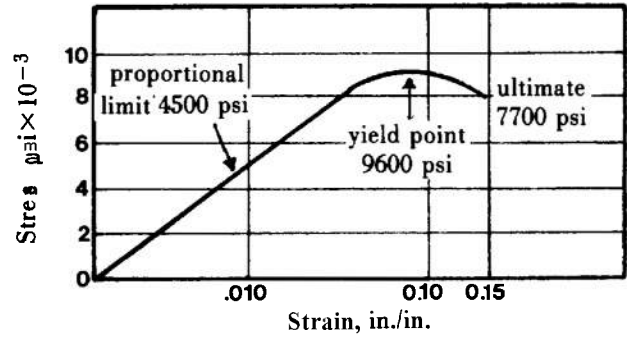
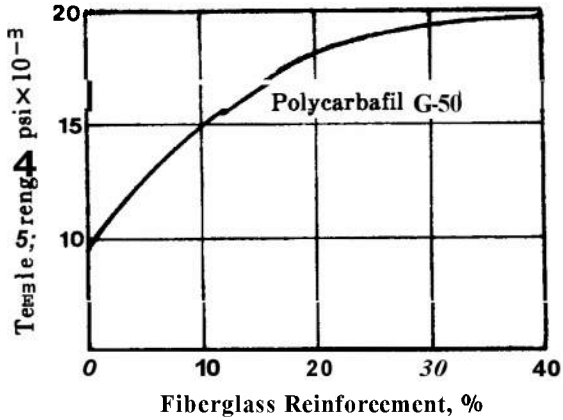
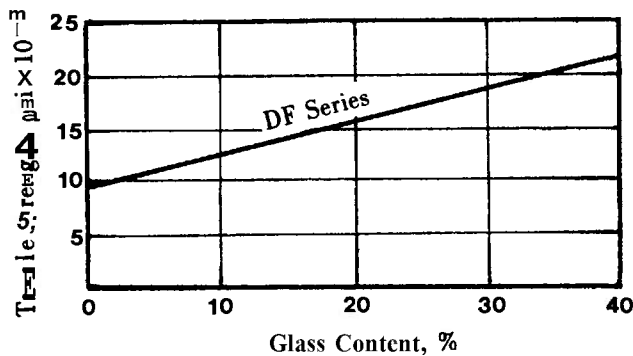
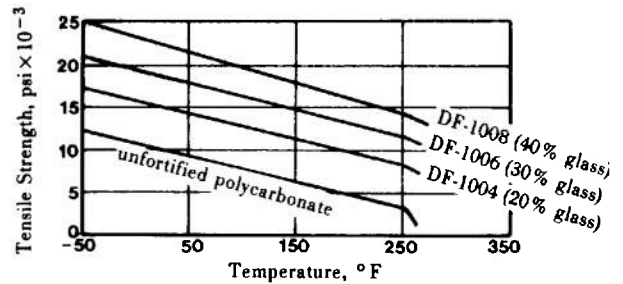


Figure 3-82. Stress-Strain Curve for Lexan 500 10% Glass Reinforced at 73°F (Ref. 26)



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Figure 3-80. Tensile Strength of Polycarbonate vs Glass Content^{27, 28}



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Figure 3-83. Tensile Strength vs Temperature for Polycarbonate²⁷

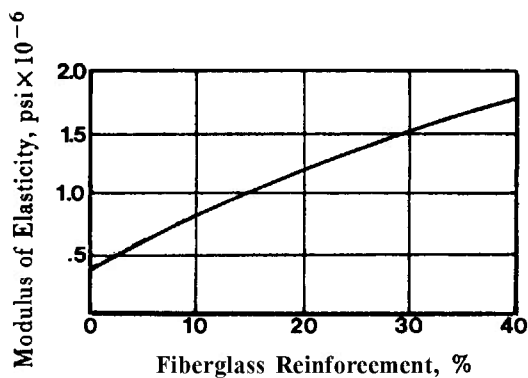
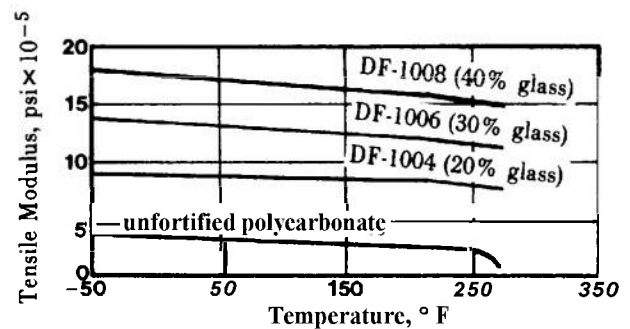
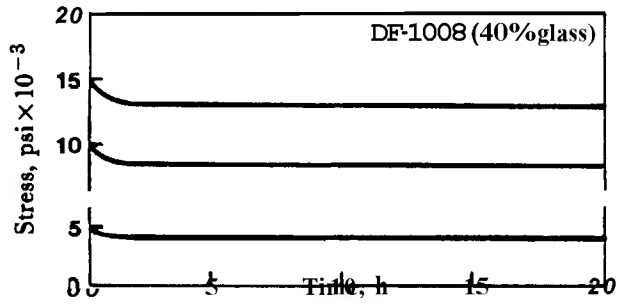


Figure 3-81. Modulus of Elasticity of Polycarbafil G 50 (Ref. 27)



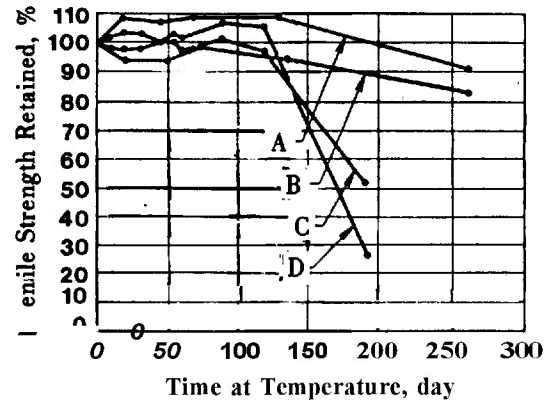
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Figure 3-84. Tensile Modulus vs Temperature of Polycarbonate²⁸



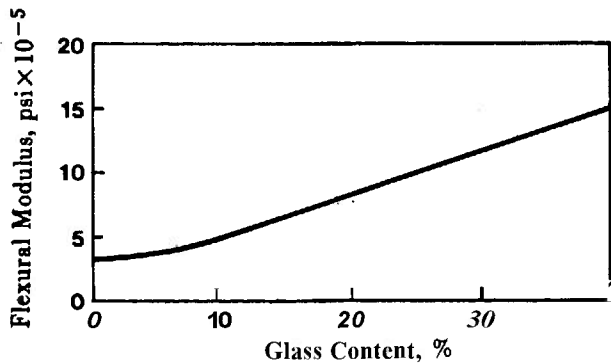
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Figure 3-85. Tensile Stress Relaxation for Polycarbonate²⁸



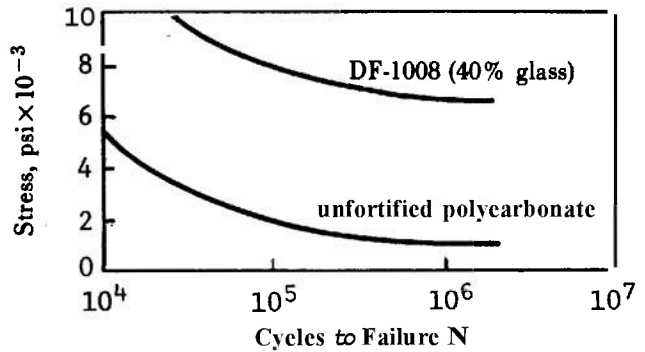
- A polycarbonate at 140° C
- B GR polycarbonate at 140° C
- C GR polycarbonate at 150° C
- D polycarbonate at 150° C

Figure 3-86. Tensile Strength Retained vs Time at 140° and 150° C for Polycarbonate²⁸



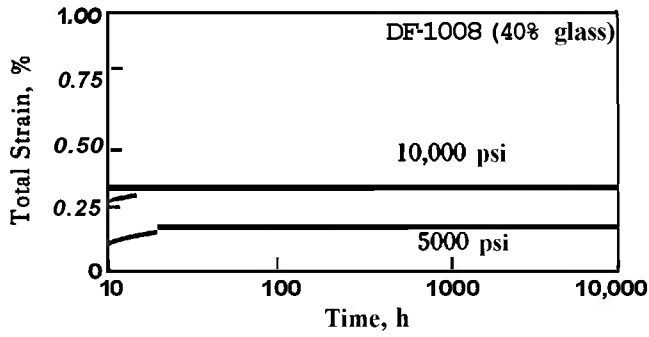
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Figure 3-87. Flexural Modulus vs Percent Glass Content for Polycarbonate Thermo-comp DF Series²⁸



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Figure 3-88. Cycles to Failure vs Alternating Flexural Stress for Polycarbonate²⁸



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Figure 3-89. Flexural Creep vs Time at 75° F for Polycarbonate²⁸

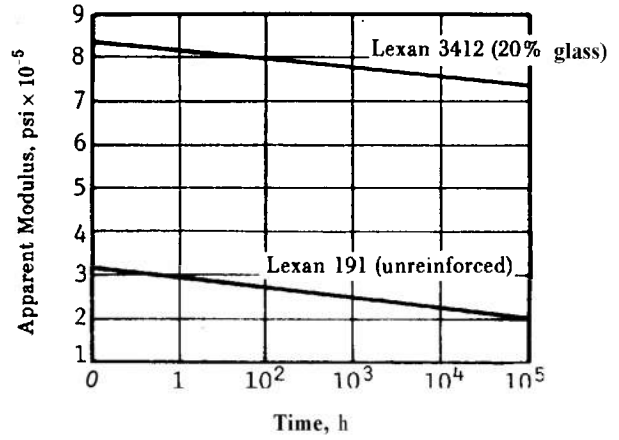


Figure 3-90. Long-Term Creep Data for Polycarbonate at 3000 psi, 70° F (Ref. 26)

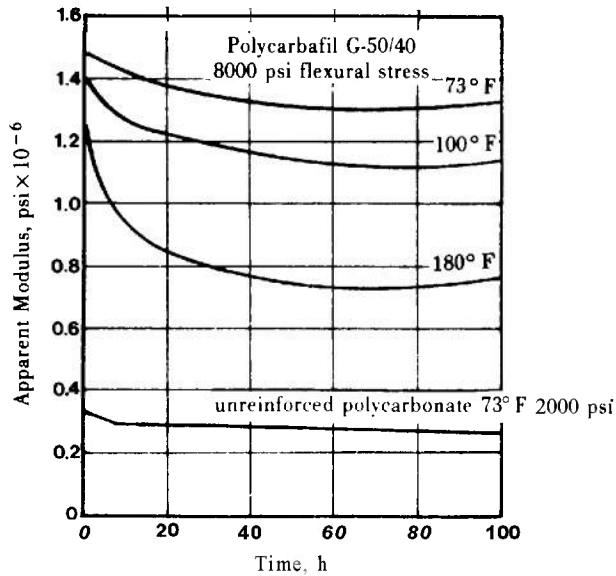


Figure 3-91. Flexural Creep—Apparent Modulus vs Time for 40% Glass-Reinforced Polycarbonateⁿ

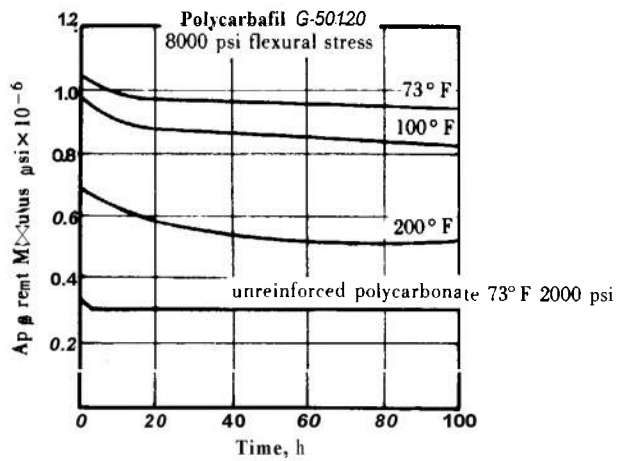
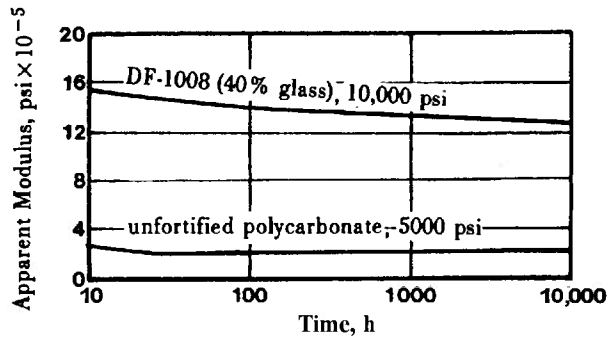


Figure 3-92. Flexural Creep—Apparent Modulus vs Time for 20% Glass-Reinforced Polycarbonate²⁷



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Figure 3-93. Flexural Creep Modulus vs Time at 75°F for Polycarbonate²⁸

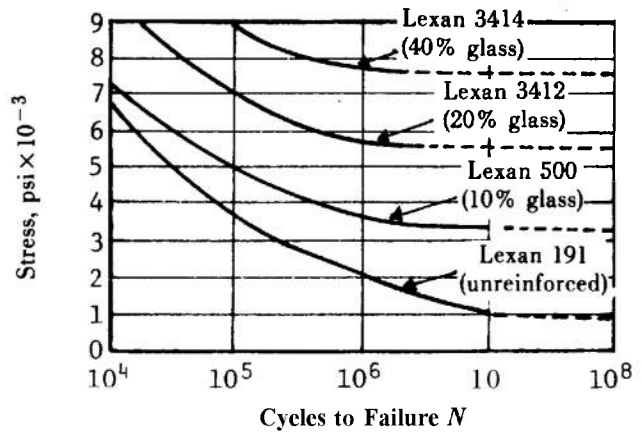


Figure 3-94. Fatigue Endurance for Polycarbonate Resins²⁶

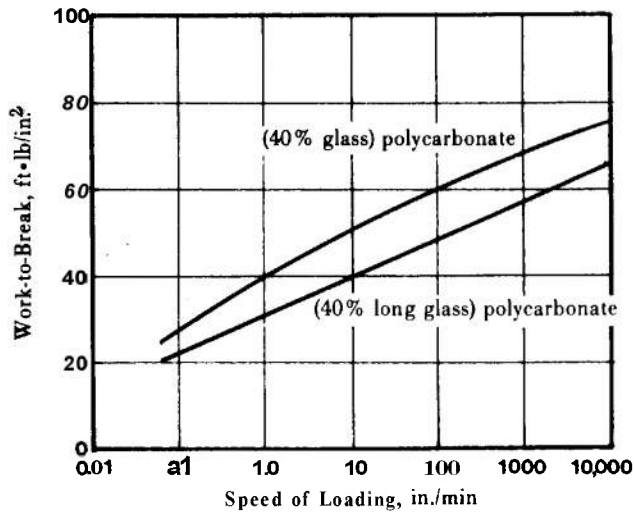


Figure 3-95. Work-to-Break as a Function of Loading Speed for Glass-Reinforced Polycarbonate Resins¹

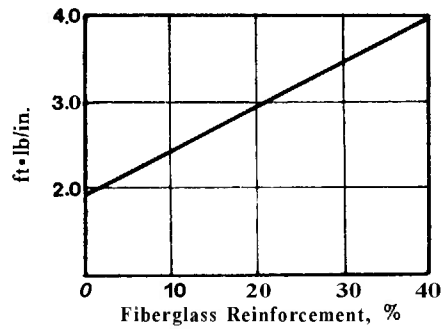


Figure 3-96. Izod Impact of Polycarbafil G 50 vs Glass²⁷

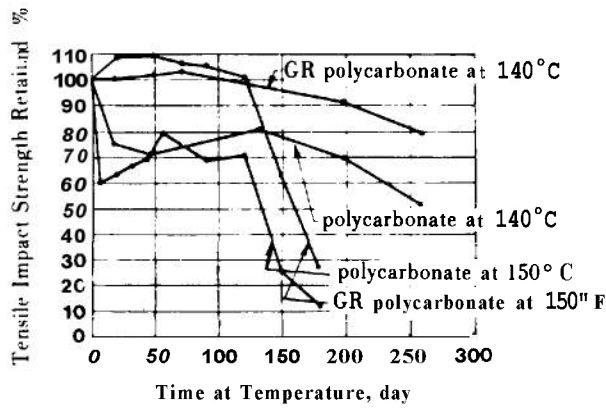


Figure 3-97. Tensile Impact Strength Retained vs Time at 140° and 150°C for Polycarbonate^B

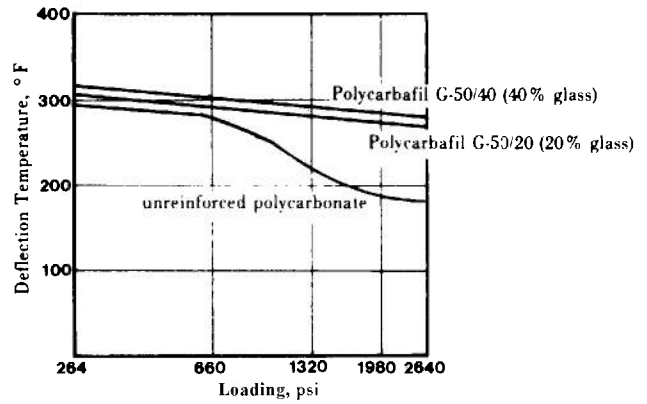
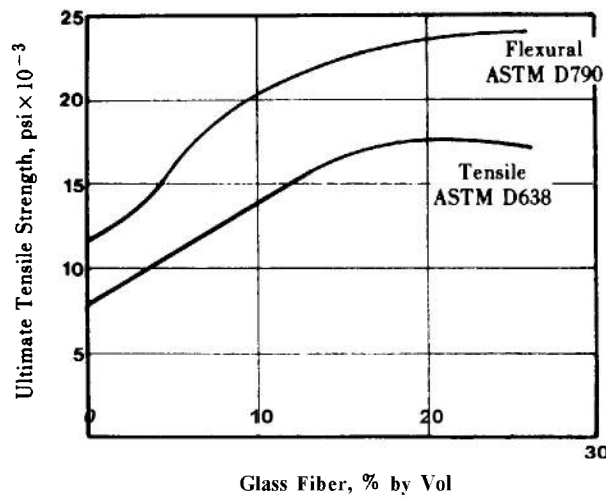
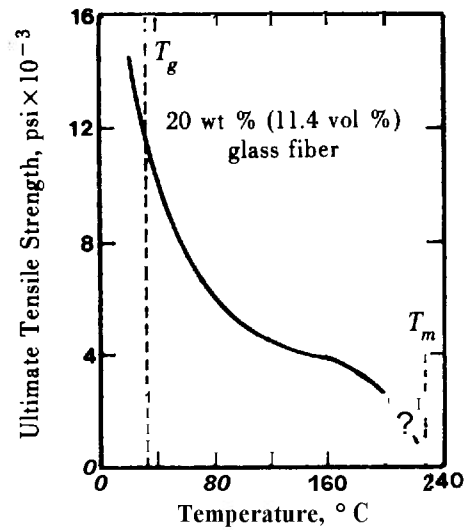


Figure 3-98. Deflection Temperature vs Loading for Polycarbonate²⁷



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Figure 3-99. Influence of Glass Fiber Concentration on Ultimate Strength of Tenite PTMT³⁰



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Figure 3-100. Influence of Temperature on Ultimate Tensile Strength of Tenite³⁰

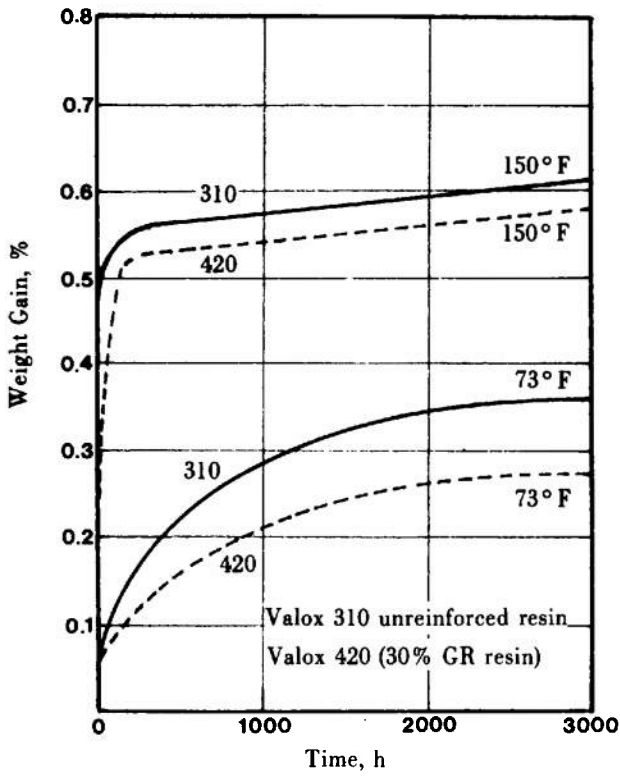
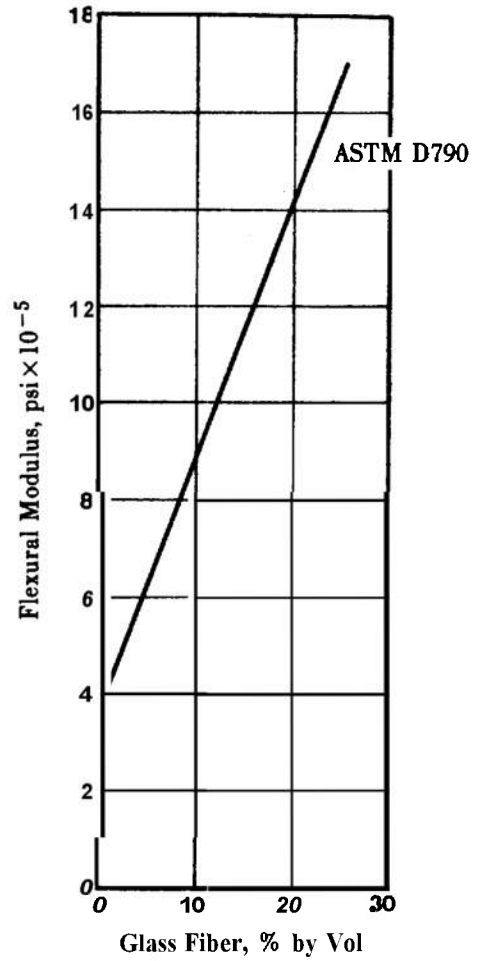
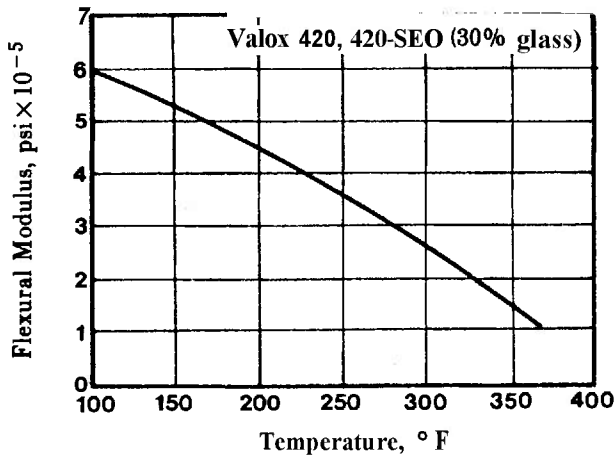


Figure 3-101. Weight Gain in Water of Valox³¹



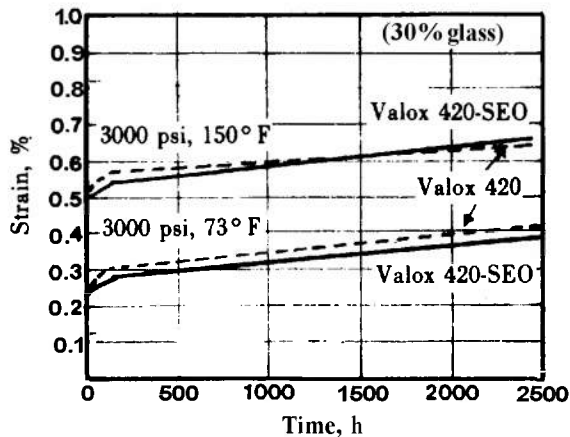
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Figure 3-102. Influence of Glass Fiber Concentration on Flexural Modulus of Tenite PTMT³⁰



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Figure 3-103. Flexural Modulus at Elevated Temperature of Polyester³²



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Figure 3-104. Flexural Creep of Polyester³²

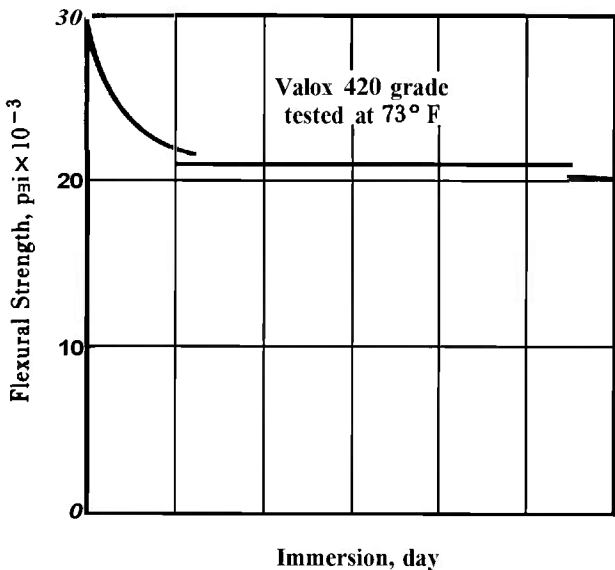
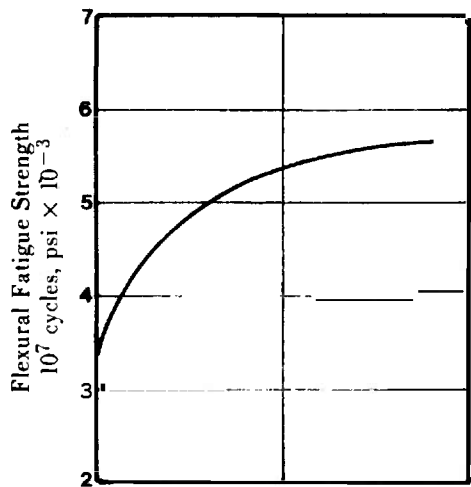
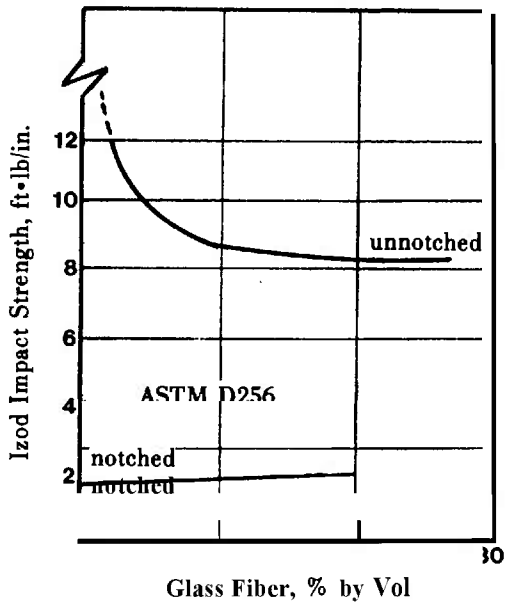


Figure 3-105. Flexural Strength vs Time in Water for Valox 30% Glass Reinforced³²



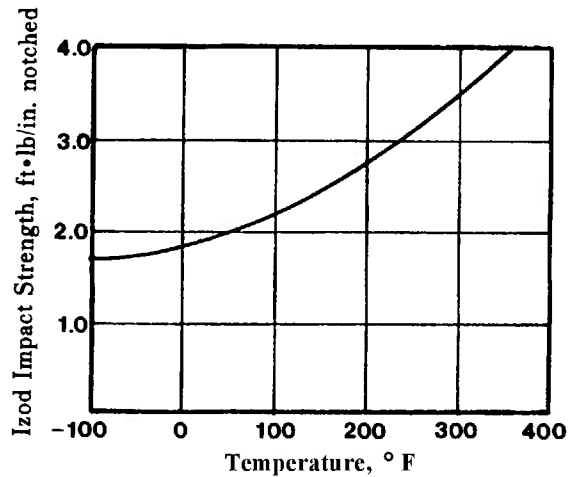
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Figure 3-106. Influence of Glass Fiber Concentration on Fatigue Resistance of Tenite PTMT³⁰



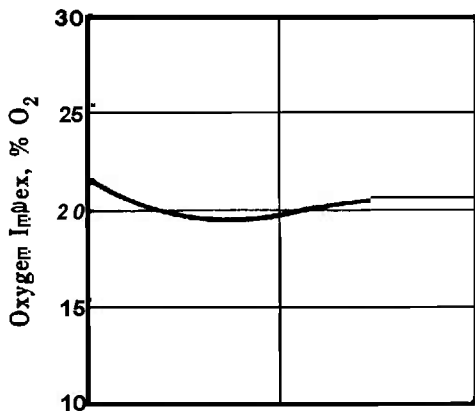
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Figure 3-107. Influence of Glass Fiber Concentration of Impact Strength on Tenite³⁰



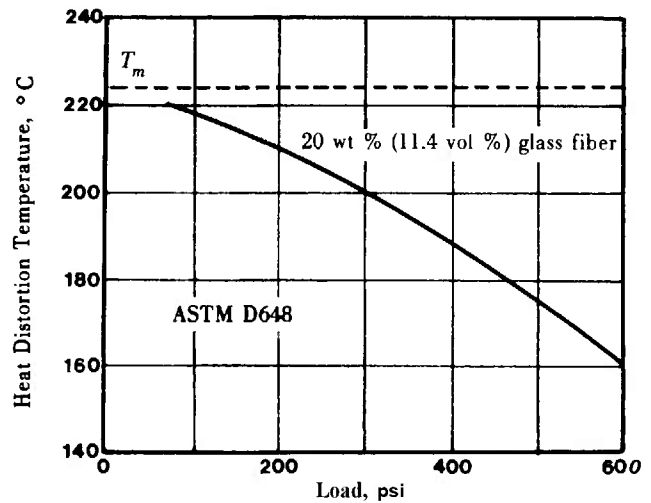
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Figure 3-108. Impact Strength vs Temperatures of Valox 420, 420-SEO (30% Glass)³²



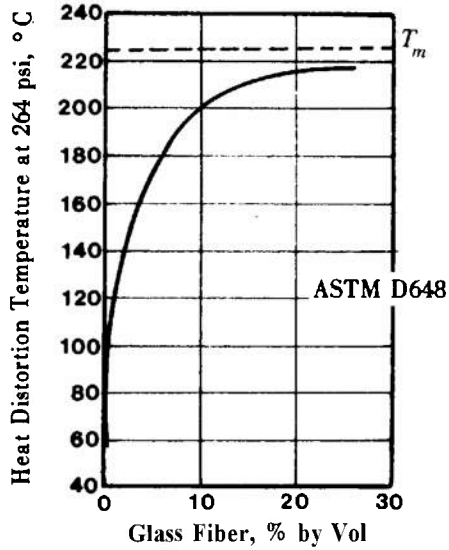
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Figure 3-109. Influence of Glass Fiber Concentration on Flammability of Tenite PTMT³⁰



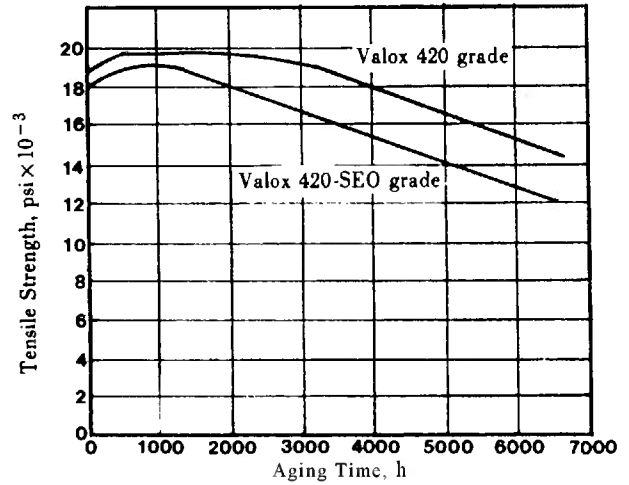
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Figure 3-110. Influence of Load on Heat Distortion Temperature of Tenite PTMT³⁰



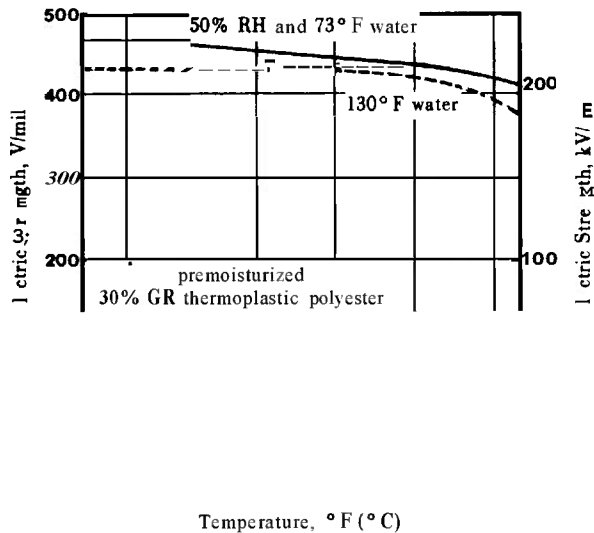
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Figure 3-111. Influence of Glass Fiber Concentration on Heat Distortion Temperature of Tenite PTMT³⁰



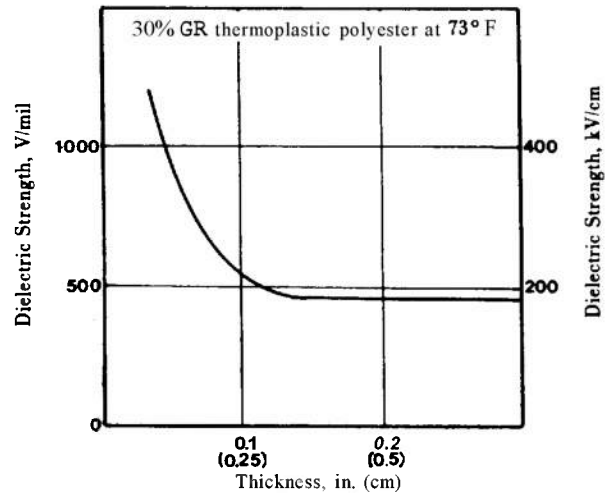
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Figure 3-112. Tensile Strength After Thermal Aging of Polyester at 160°C (Ref. 32)



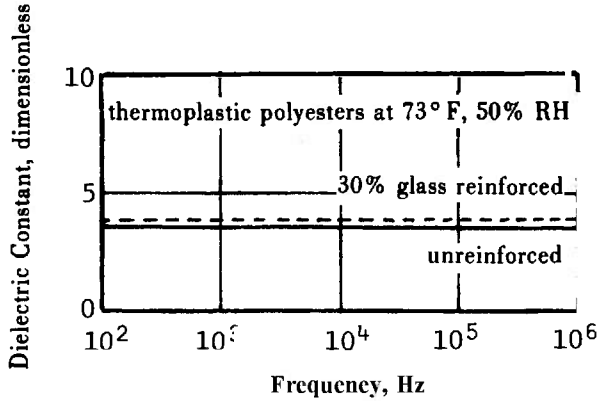
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Figure 3-113. Dielectric Strength vs Temperature of Premoisturized Valox³¹



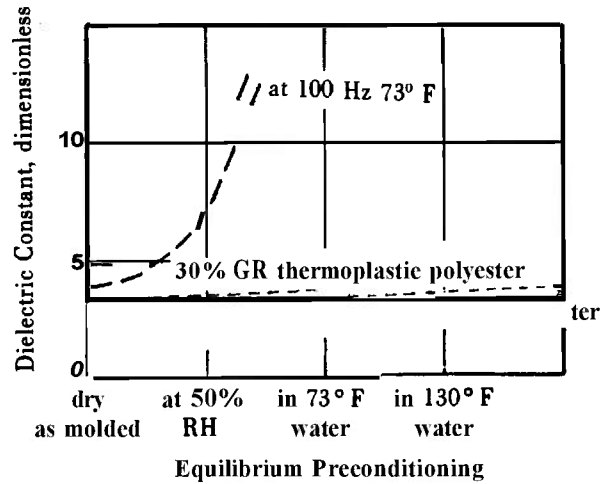
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Figure 3-114. Dielectric Strength vs Thickness of Valox³¹



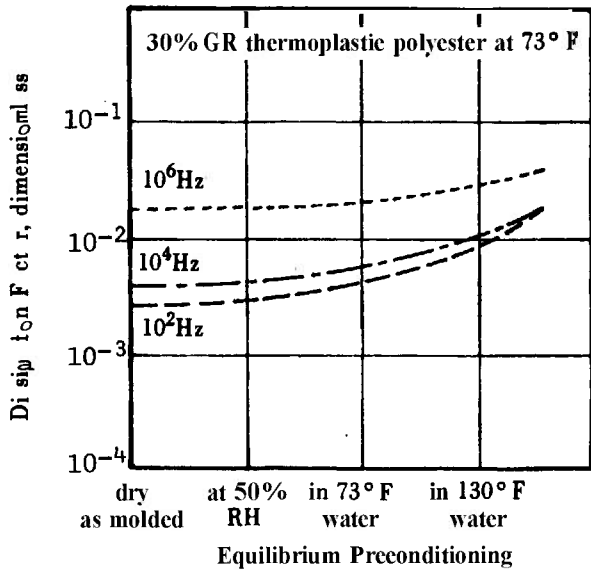
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Figure 3-115. Dielectric Constant of Valox as a Function of Frequency"



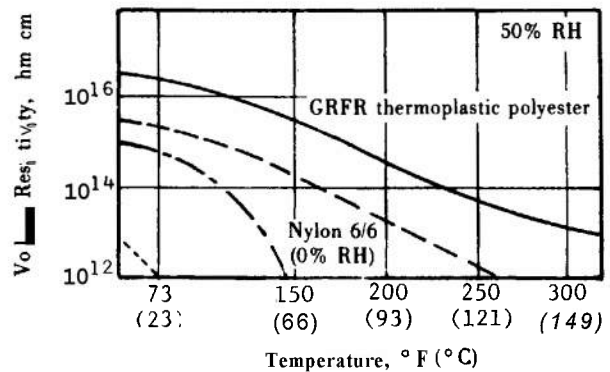
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Figure 3-116. Dielectric Constant of Valox vs Moisture³¹



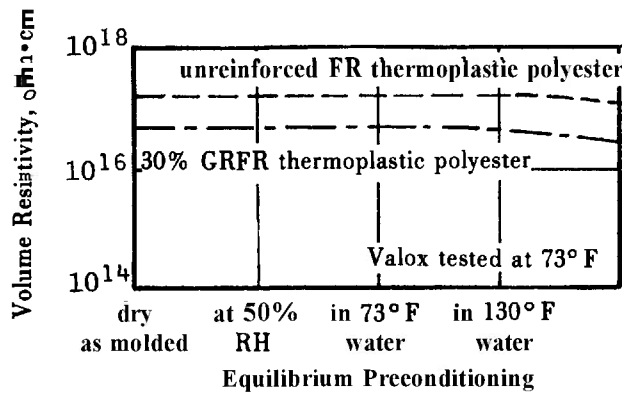
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Figure 3-117. Dissipation Factor vs Valox Moisture and Frequency of Valox³¹



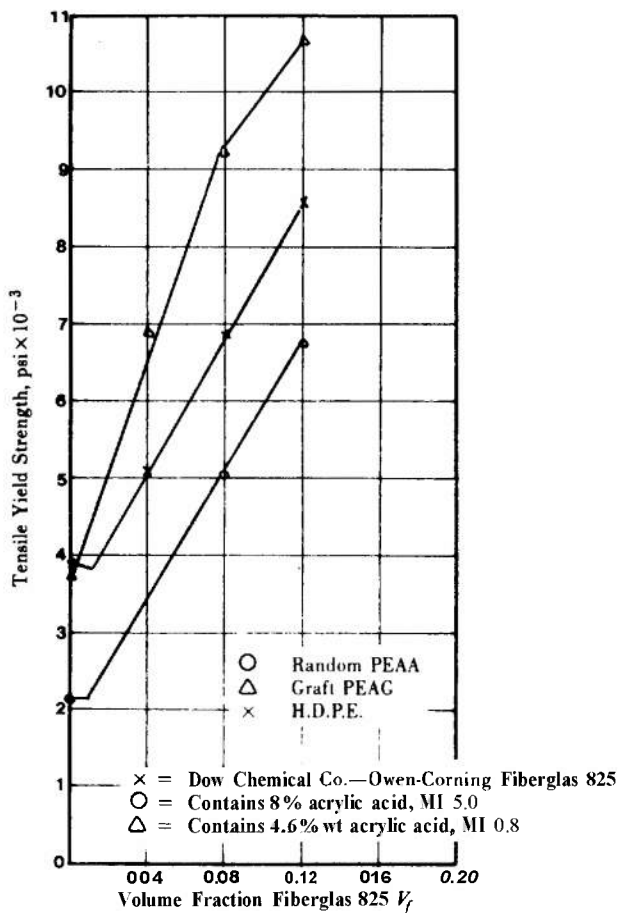
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Figure 3-118. Volume Resistivity vs Temperature of Valox³¹



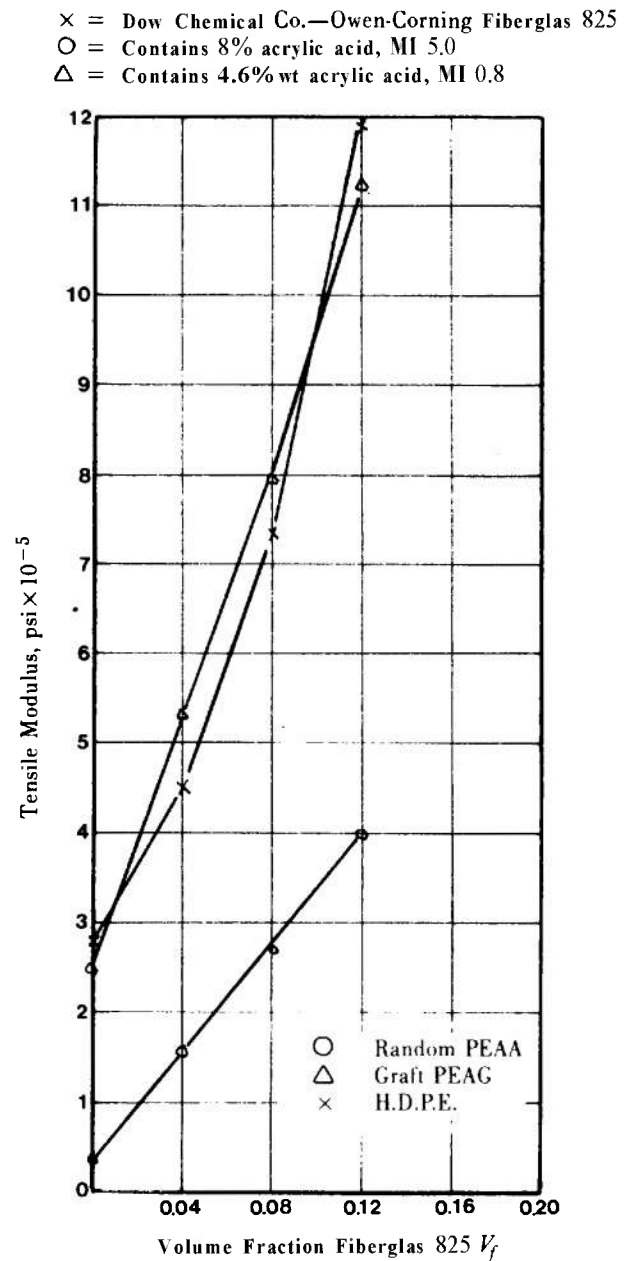
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Figure 3-119. Volume Resistivity vs Moisture and Temperature of Valox³¹



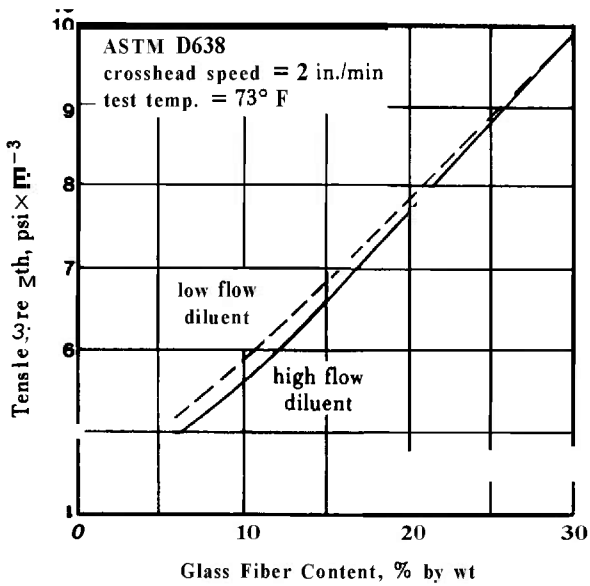
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Figure 3-120. Tensile Strength of Injection Molded Polyethylene and Ethylene-Acrylic Acid Copolymers vs Glass Content³⁴



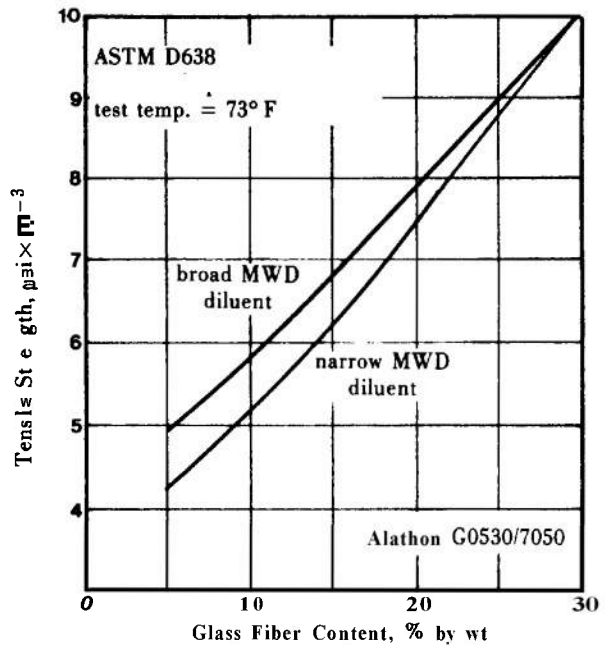
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Figure 3-121. Tensile Modulus of Injection Molded Polyethylene and Ethylene-Acrylic Acid Copolymers vs Glass Content³⁴



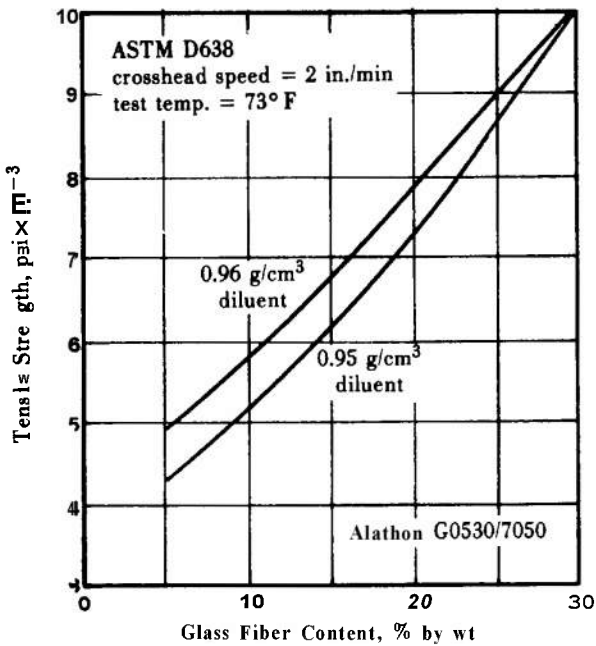
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Figure 3-122. Effect of Diluent Melt Flow on Tensile Strength of Various Glass-Filled PE (Diluent MWD and density held constant.)%



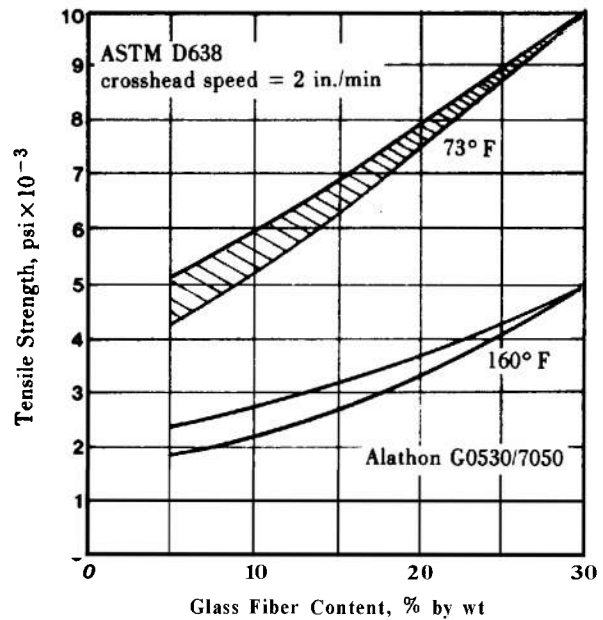
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Figure 3-123. Effect of Diluent MWD on Tensile Strength of Various Glass-Filled PE (Diluent density and melt flow held constant.)%



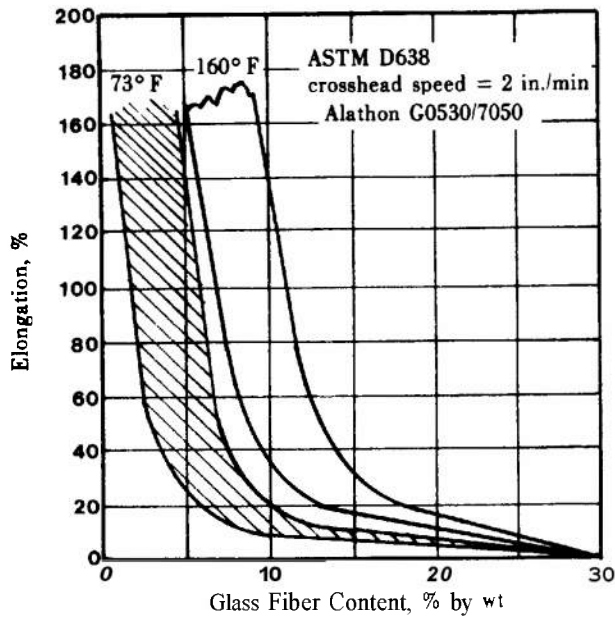
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Figure 3-124. Effect of Diluent Density on Tensile Strength of Various Glass-Filled PE (Diluent MWD and melt flow held constant.)³⁶



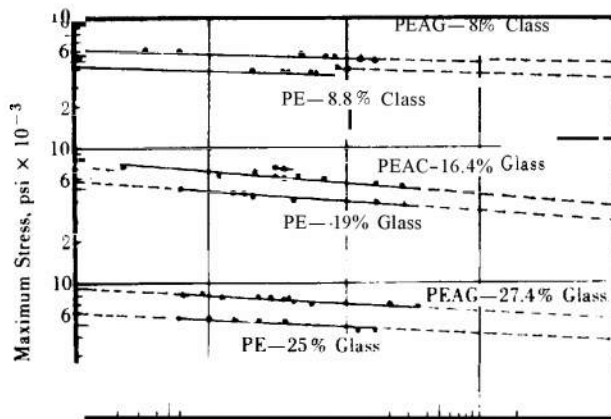
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Figure 3-125. Tensile Strength vs Glass Fiber Content of PE³⁶



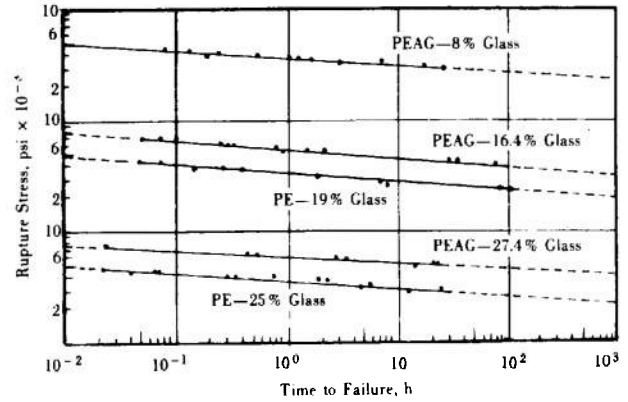
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Figure 3-126. Elongation vs Glass Fiber Content of PE³⁶



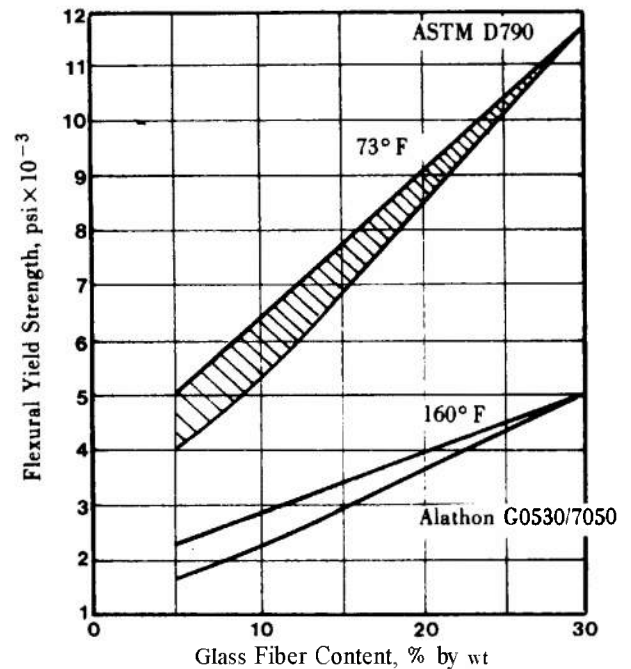
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Figure 3-128. Cyclic Tensile Fatigue of Glass-Reinforced Polyethylene and Polyethylene-Acrylic Acid Graft Copolymers³⁴



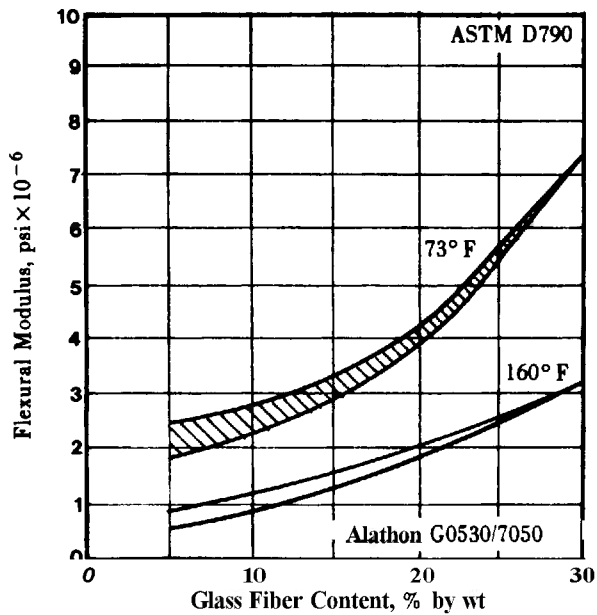
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Figure 3-127. Stress Rupture for Glass-Reinforced Polyethylene and Polyethylene-Acrylic Acid Graft Copolymers³⁴



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Figure 3-129. Flexural Yield Strength vs Glass Fiber Content of PE³⁶



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Figure 3-130. Flexural Modulus vs Glass Fiber Content of PE³⁶

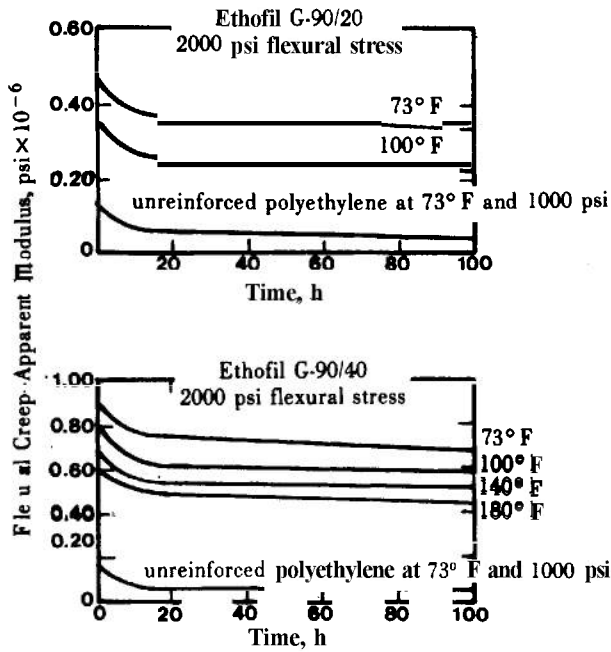
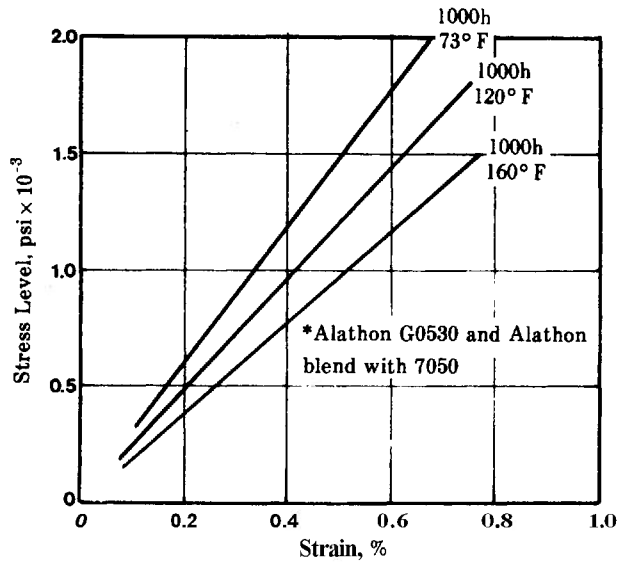
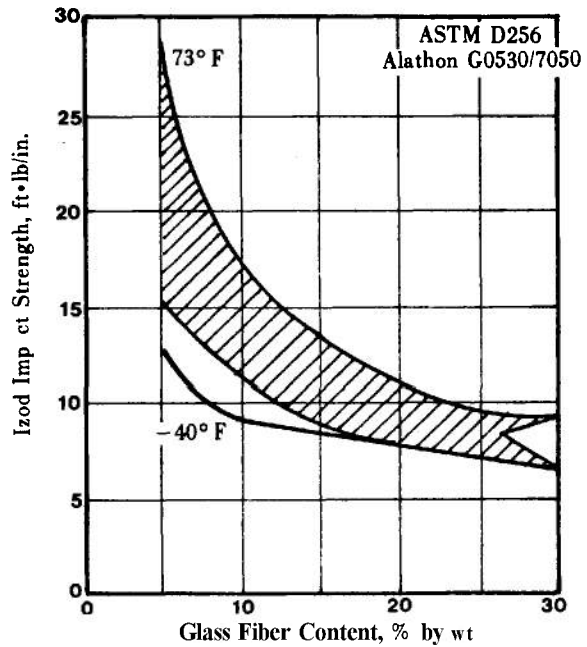


Figure 3-132. Flexural Creep—Apparent Modulus vs Time of 20% and 40% Glass-Reinforced PE⁴⁸



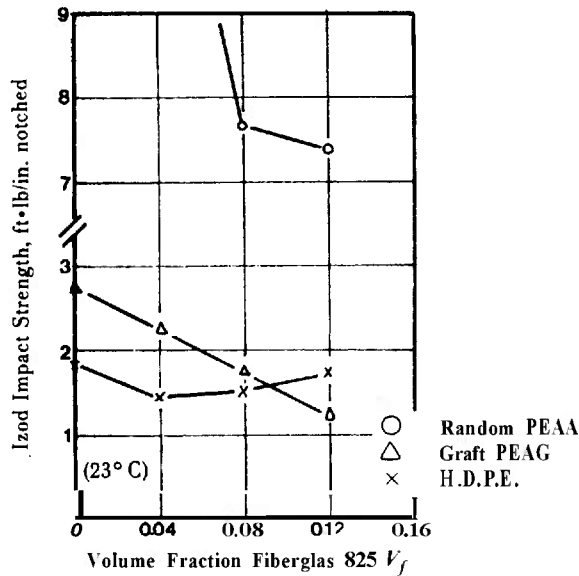
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Figure 3-131. Flexural Creep of Alathon G0530*³⁶



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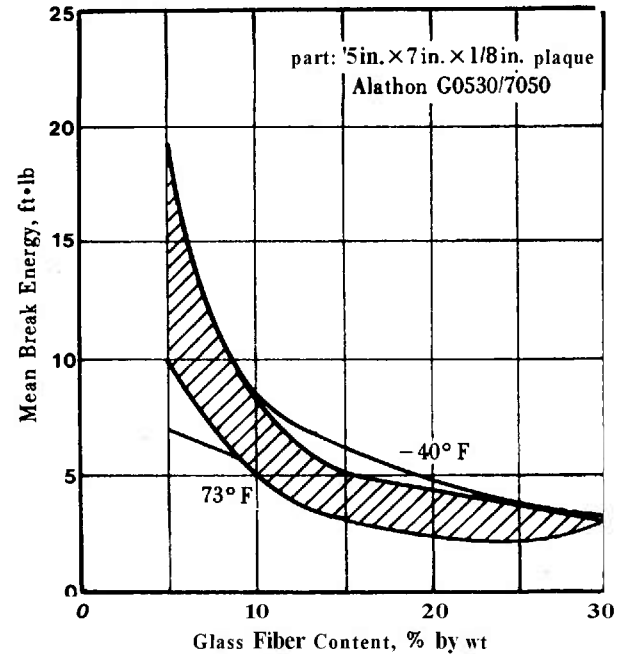
Figure 3-133. Unnotched Izod Impact Strength vs Glass Fiber Content of PE³⁶



- × = Dow Chemical Co.—Owen-Corning Fibreglas 825
- = Contains 8% acrylic acid, MI 5.0
- △ = Contains 4.6%wt acrylic acid, MI 0.8

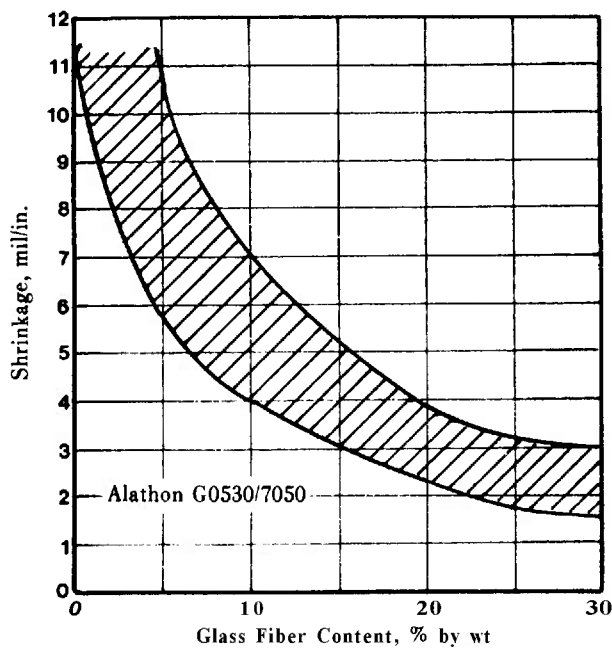
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Figure 3-134. Impact Strength of Injection Molded Polyethylene and Ethylene-Acrylic Acid Copolymers vs Glass Content³⁴



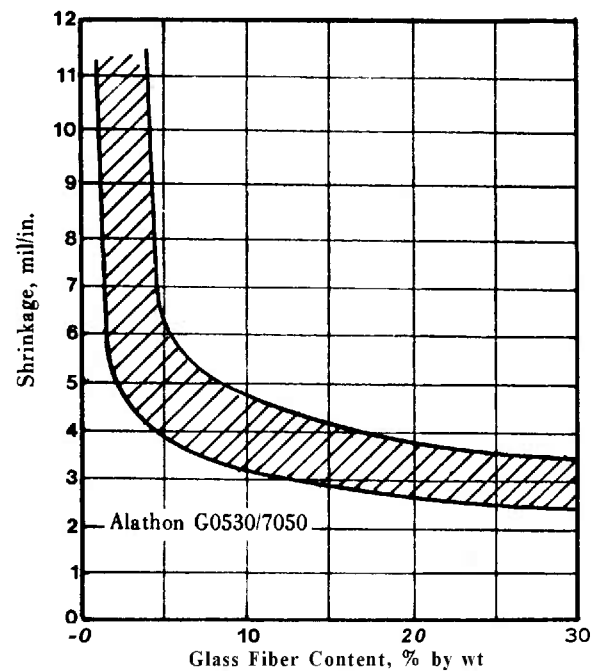
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Figure 3-135. Dart Drop Impact Strength vs Glass Fiber Content of PE³⁶



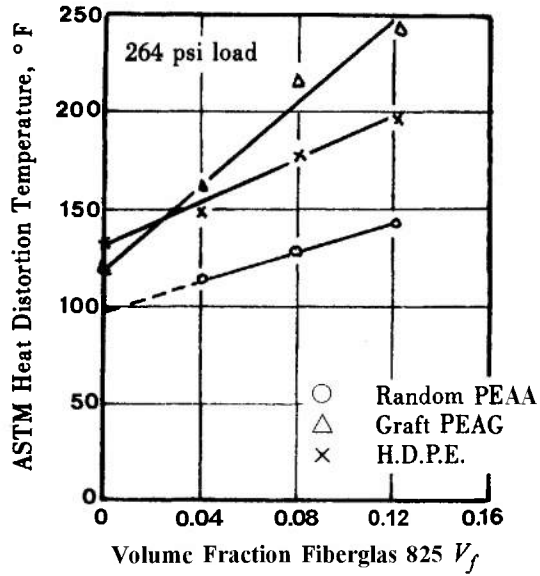
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Figure 3-136. Shrinkage in the Machine Direction vs Glass Fiber Content of PE³⁶



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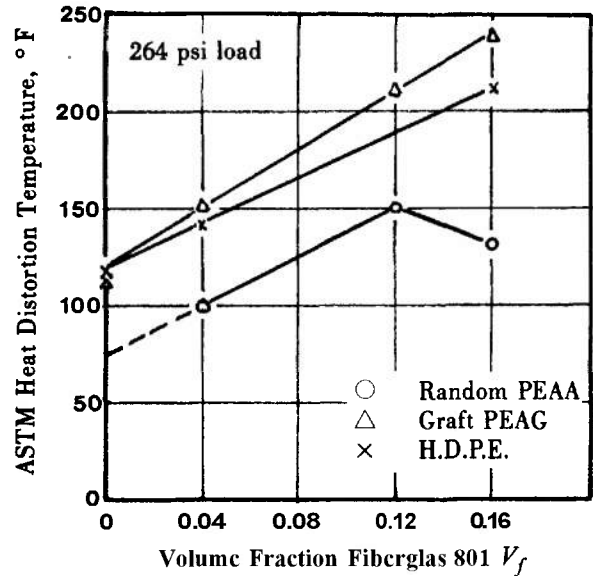
Figure 3-137. Shrinkage in the Transverse Direction vs Glass Fiber Content of PE³⁶



× = Dow Chemical Co.—Owen-Corning Fiberglas 825
 ○ = Contains 8% acrylic acid, MI 5.0
 △ = Contains 4.6% wt acrylic acid, MI 0.8

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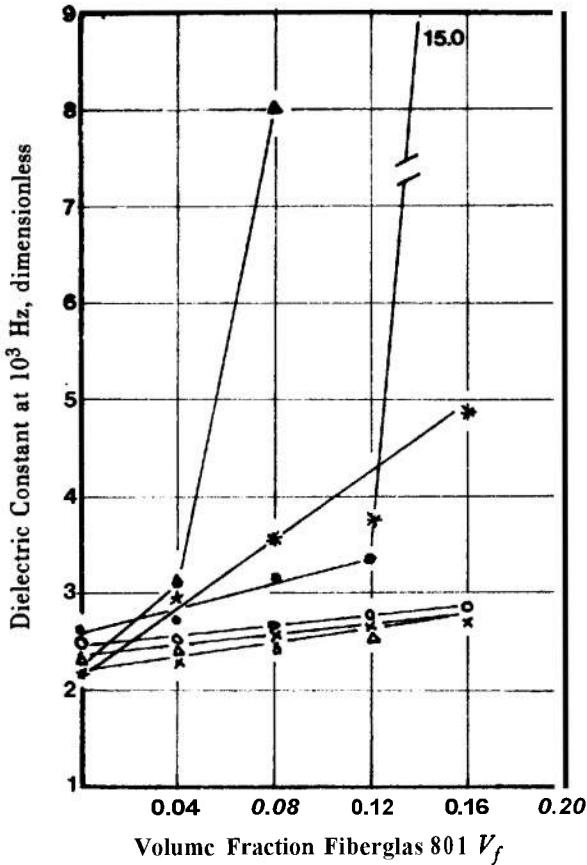
Figure 3-138. Heat Distortion Temperature vs Glass Content of Polyethylene and Ethylene-Acrylic Acid Copolymers (Injection Molded)³⁴



× = Dow Chemical Co.—Owen-Corning Fiberglas 825
 ○ = Contains 8% acrylic acid, MI 5.0
 △ = Contains 4.6% wt acrylic acid, MI 0.8

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Figure 3-139. Heat Distortion Temperature vs Glass Content of Polyethylene and Ethylene-Acrylic Acid Copolymers (Compression Molded)³⁴

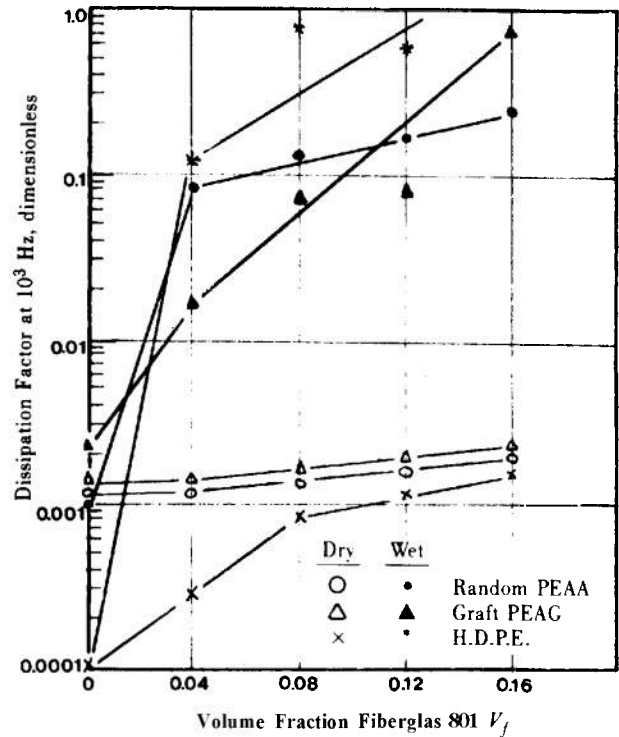


Dry		Wet		
O	•	•	•	Random PEAA
Δ	▲	▲	▲	Graft PEAG
X	*	*	*	H.D.P.E.

X = Dow Chemical Co.—Owen-Corning Fiberglas 825
 O = Contains 8% acrylic acid, MI 5.0
 Δ = Contains 4.6% wt acrylic acid, MI 0.8

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Figure 3-140. Dielectric Constant vs Glass Content of Polyethylene and Ethylene-Acrylic Acid Copolymers (Compression Molded) (ASTM D150-64T at 1000 Hz)³⁴



X = Dow Chemical Co.—Owen-Corning Fiberglas 825
 O = Contains 8% acrylic acid, MI 5.0
 Δ = Contains 4.6% wt acrylic acid, MI 0.8

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Figure 3-141. Dissipation Factor vs Glass Content of Polyethylene and Ethylene-Acrylic Acid Copolymers (Compression Molded) (ASTM D150-64T at 1000 Hz)³⁴

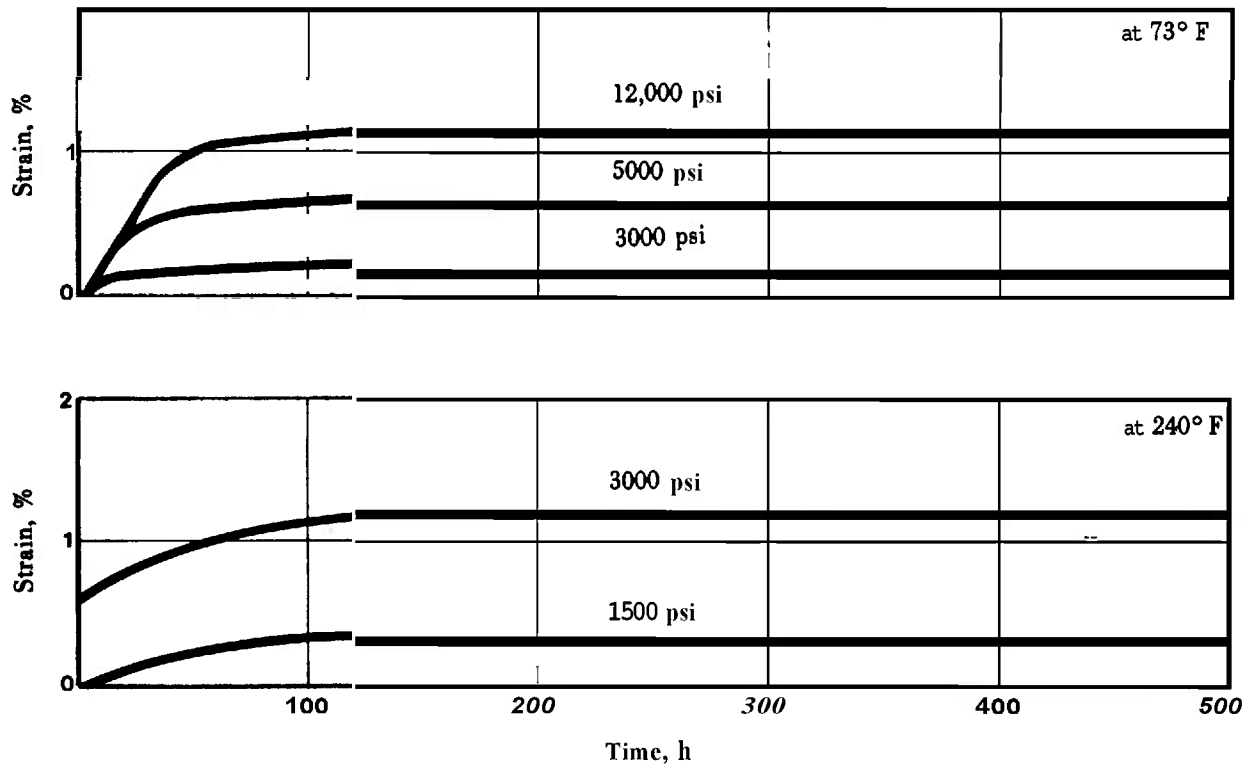


Figure 3-142. Tensile Creep of 30% Glass-Reinforced Noryl GFN3 of 73° and 240° F (Ref. 37)

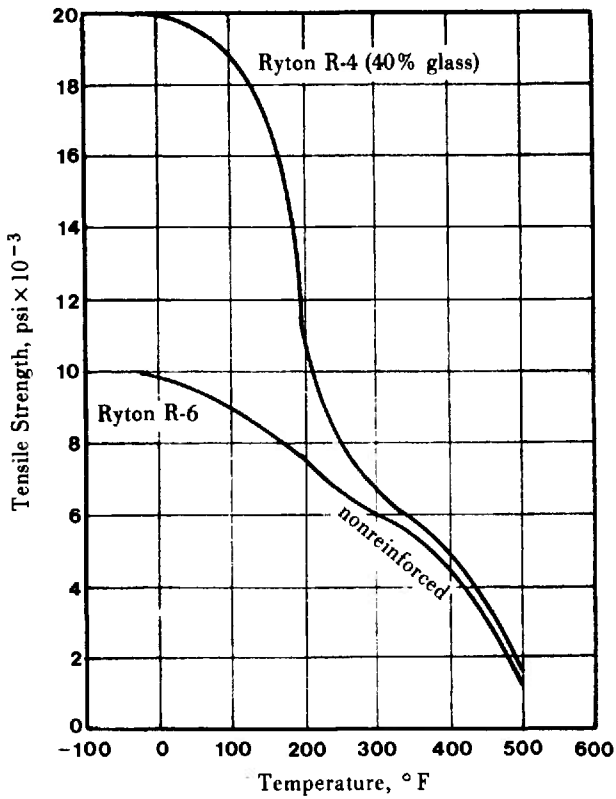


Figure 3-143. Tensile Strength vs Temperature of Ryton³⁸

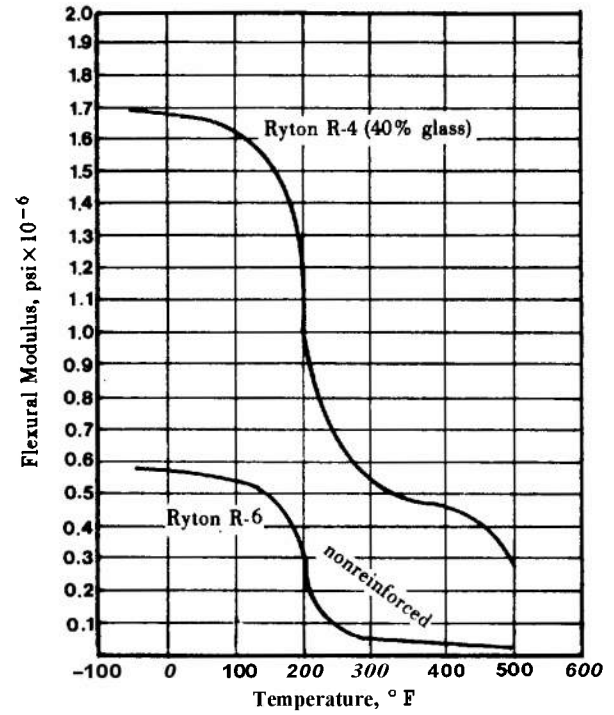


Figure 3-144. Flexural Modulus vs Temperature of Ryton³⁸

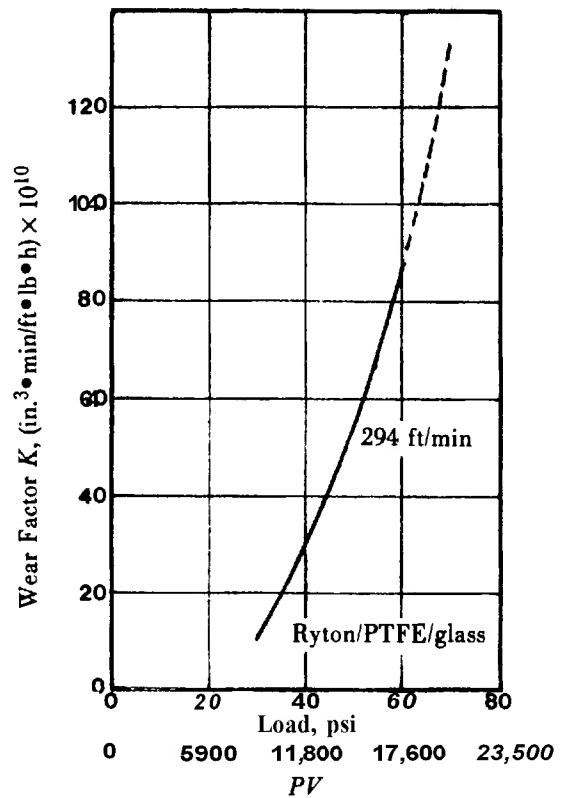


Figure 3-145. Wear Factor vs Load at 294 fpm for Ryton³⁹

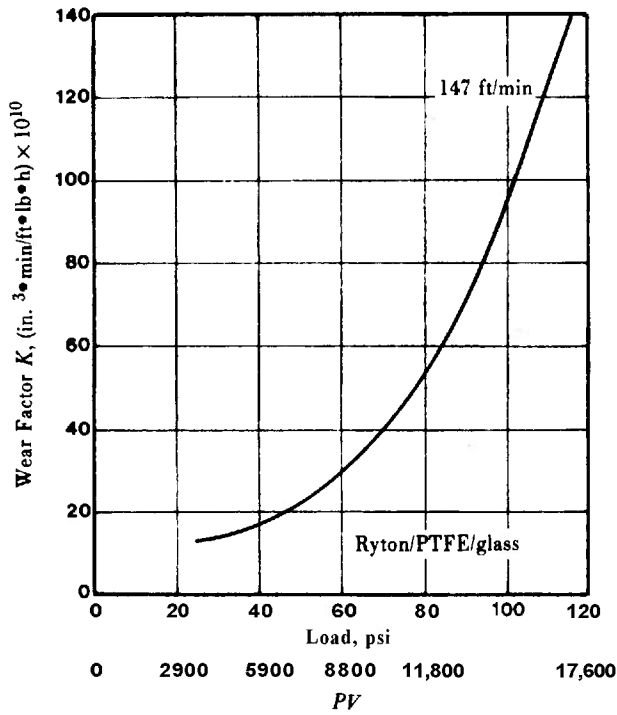


Figure 3-146. Wear Factor vs Load at 147 fpm for Ryton³⁹

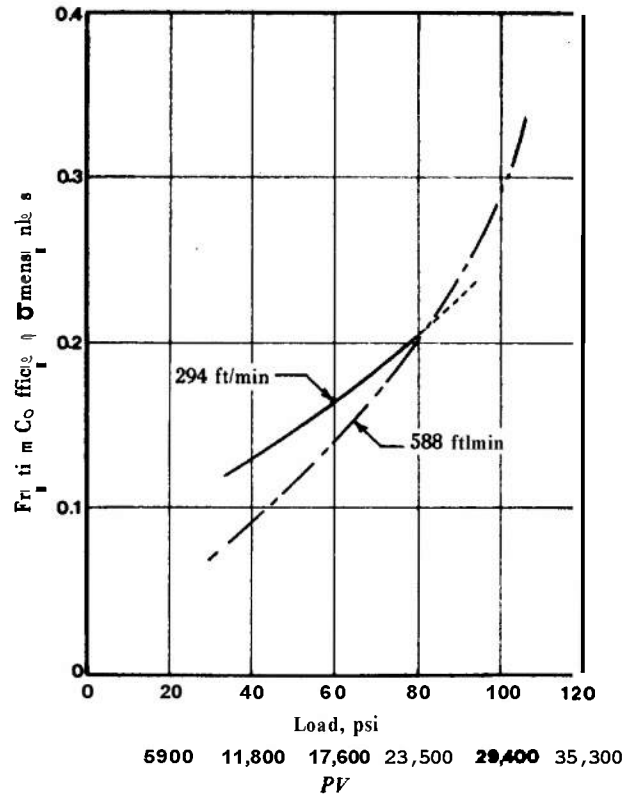


Figure 3-147. Friction Coefficient vs Load at 294 and 588 fpm for Ryton/PTFE/Fiberglass³⁹

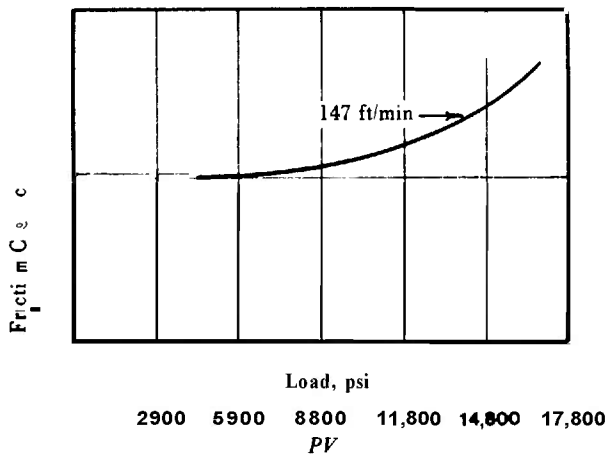


Figure 3-148. Friction Coefficient vs Load at 147 fpm for Ryton/PTFE/Fiberglass³⁹

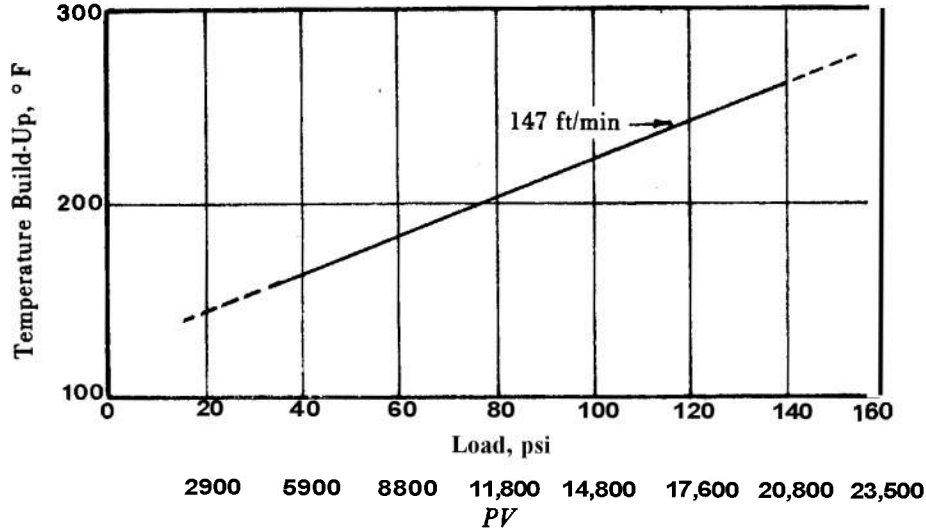


Figure 3-149. Bearing Temperature Build-Up vs Load at 147 fpm for Ryton/PTFE/Fiberglass³⁹

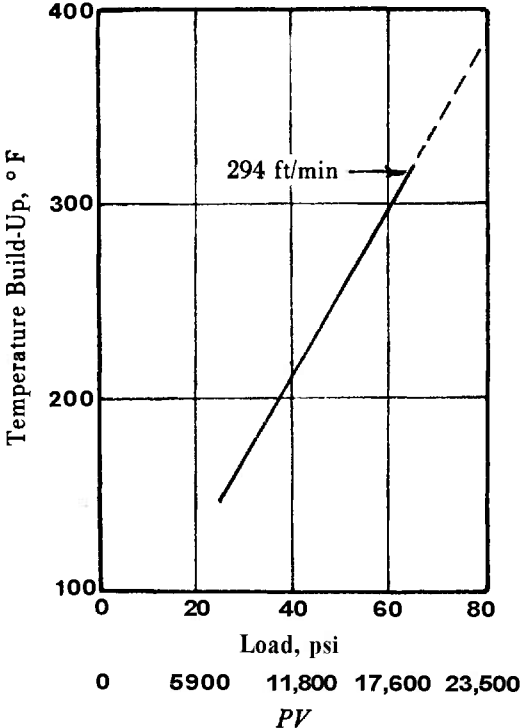


Figure 3-150. Bearing Temperature Build-Up vs Load at 294 fpm for Ryton/PTFE/Fiberglass³⁹

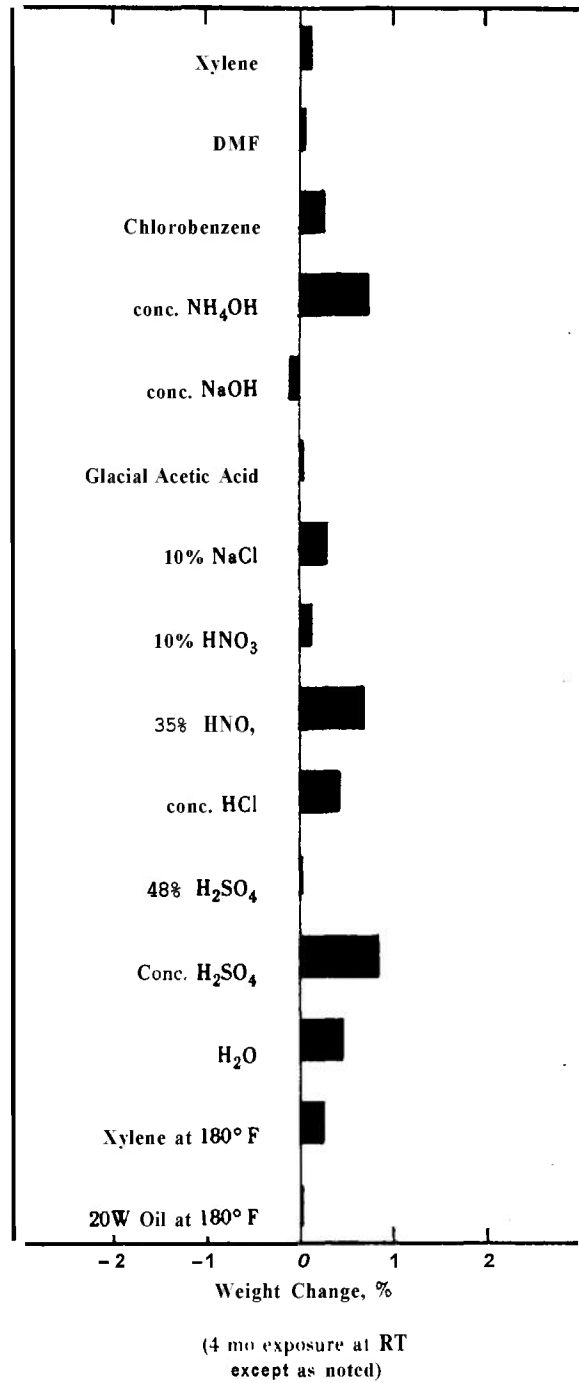
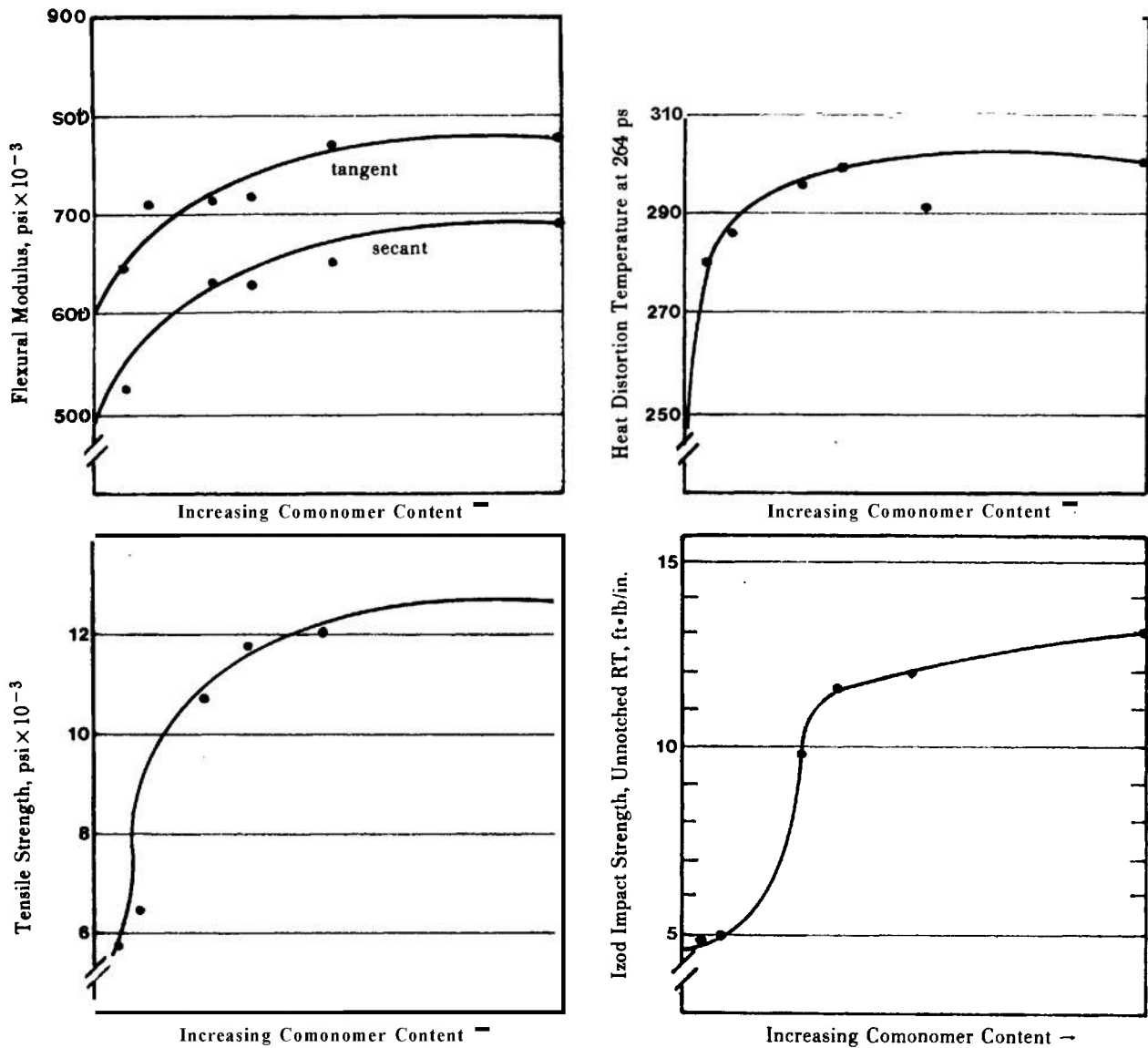


Figure 3-151. Chemical Resistance of Ryton R-4 (Ref. 38)



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Figure 3-152. Effect of Acid Comonomer Content on Mechanical Properties of 30% Glass Fiber-Filled Propylene/Acid Copolymer⁴¹

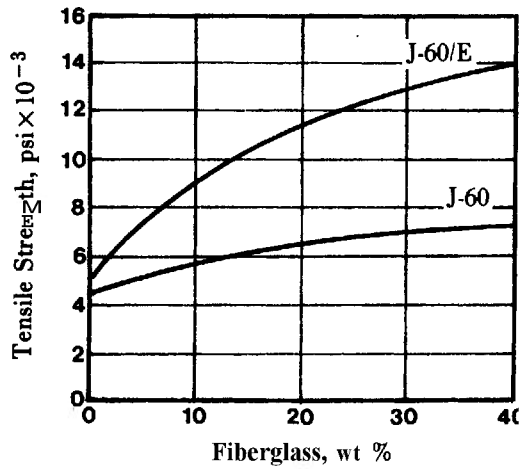
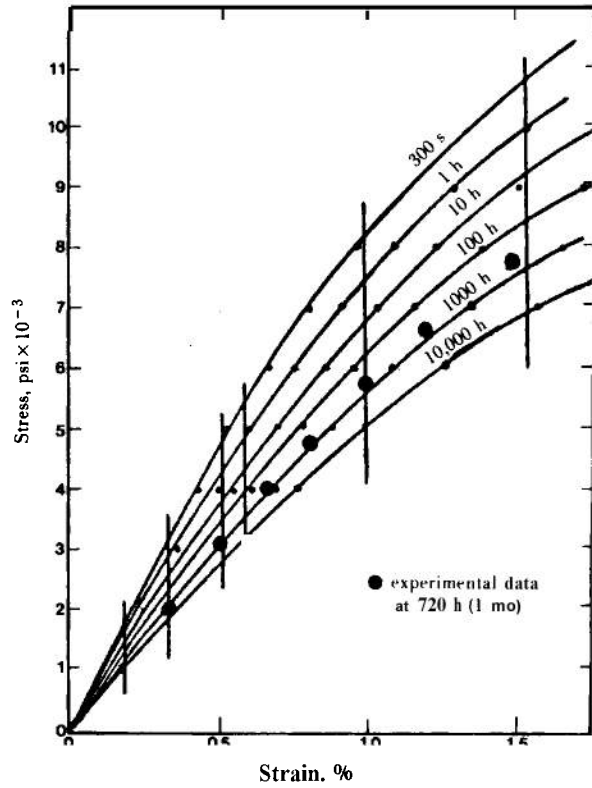
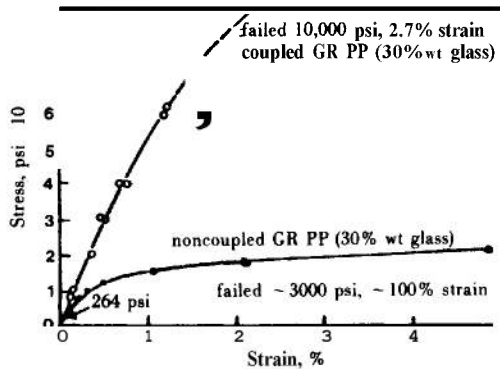


Figure 3-153. Tensile Strength vs Glass Content for Profil J-60 (Ref. 43)



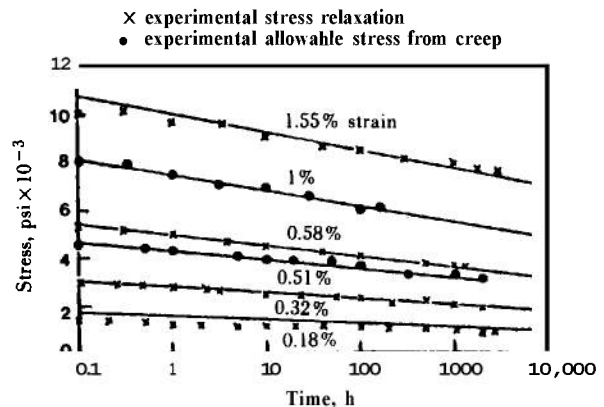
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Figure 3-154. Isochronous Stress-Strain Curves for GRPP at 73°F, 30 Weight % Glass⁴²



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Figure 3-155. Isochronous Stress-Strain Curves at 176°F for 30% Coupled GRPP⁴²



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Figure 3-156. Isometric Creep Curves and Stress Relaxation of Coupled GRPP Profax at 73°F, 30 Weight % Glass⁴²

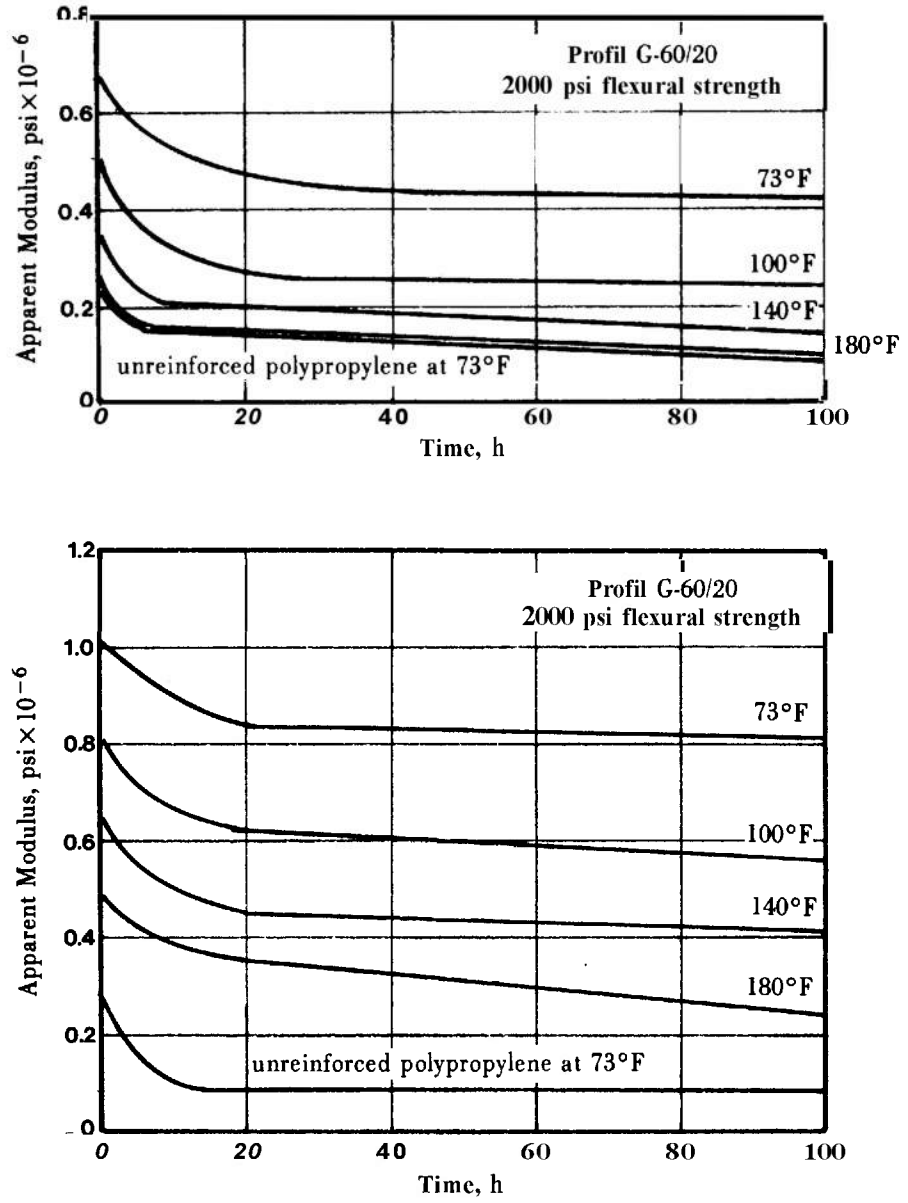
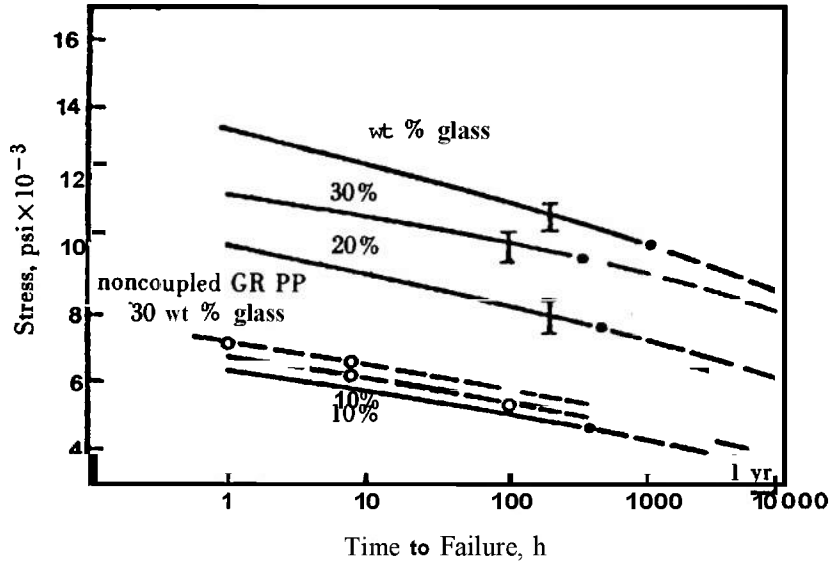


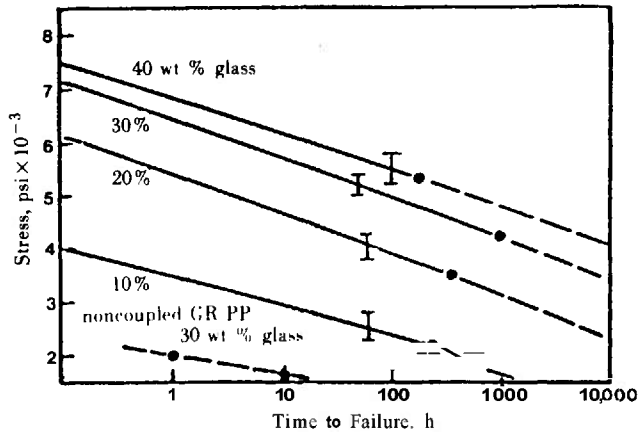
Figure 3-157. Flexural Creep – Apparent Modulus vs Time for 20% and 40% Glass-Reinforced Polypropylene⁴³



--- = extrapolations to 1 year of loading
 noncoupled GRPP = Profax 6324 + 30 weight % Owens Corning Fiber 885AA

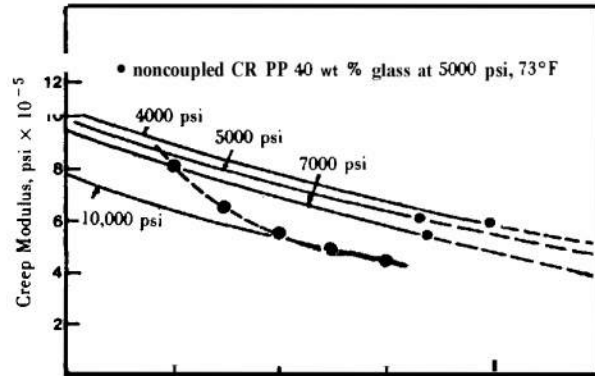
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Figure 3-158. Creep Failure Times of Coupled GRPP Profax at 73°F and 176°F (Ref. 42)



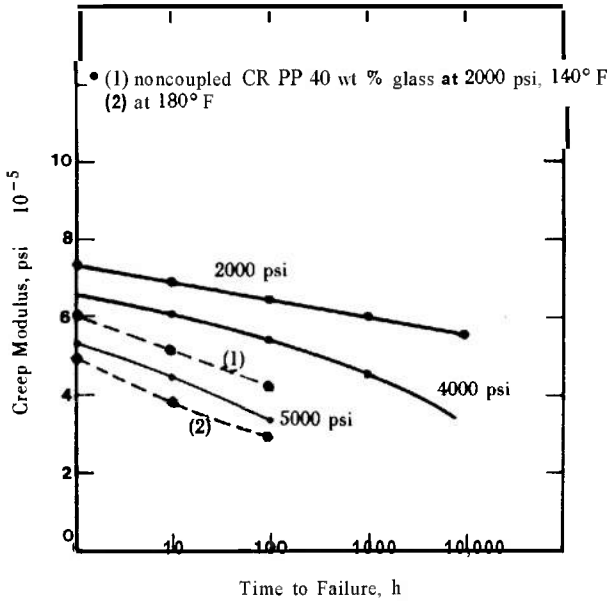
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Figure 3-159. Creep Failure Times of Coupled GRPP Profax at 176°F (Ref. 42)



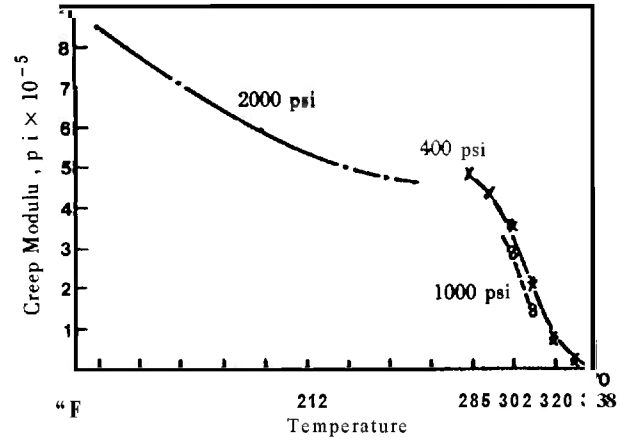
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Figure 3-160. Creep Modulus of GRPP at 73°F, 40 Weight % Glass⁴²



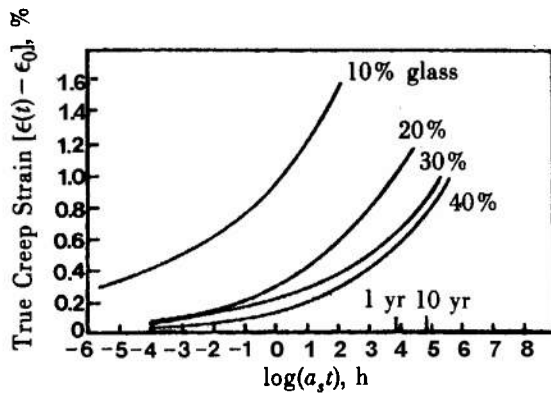
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Figure 3-161. Creep Modulus of Coupled GRPP at 176°F, 40 Weight % Glass⁴²



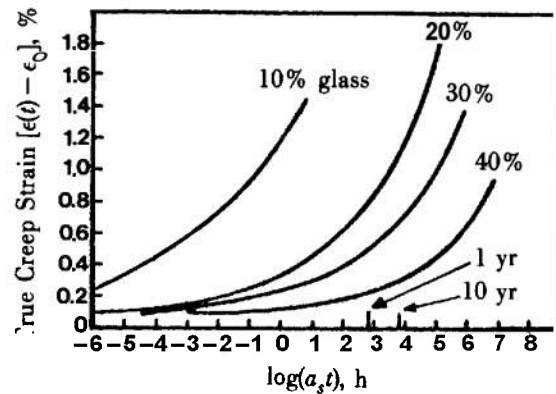
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Figure 3-162. Creep Modulus of Coupled GRPP After 100 s, 30 Weight % Glass⁴²



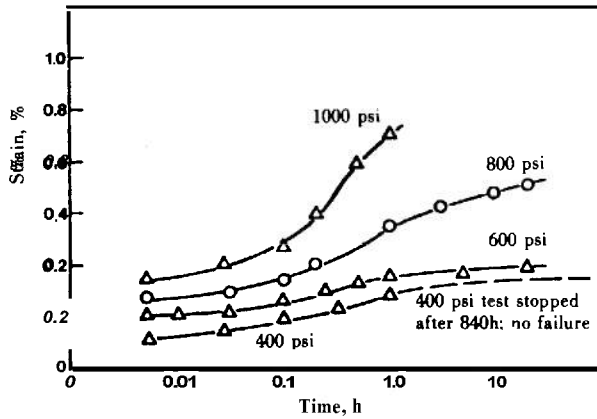
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Figure 3-163. Creep Master Curves for Coupled GRPP Profax at 73°F, 5000 psi Stress⁴²



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Figure 3-164. Creep Master Curves for Coupled GRPP Profax at 176°F, 2500 psi Stress⁴²



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Figure 3-165. Creep of Coupled GRPP at 302°F (Ref. 42)

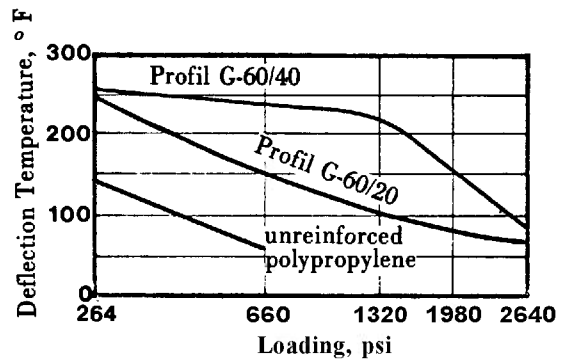


Figure 3-166. Deflection Temperature vs Loading of Profil⁴³

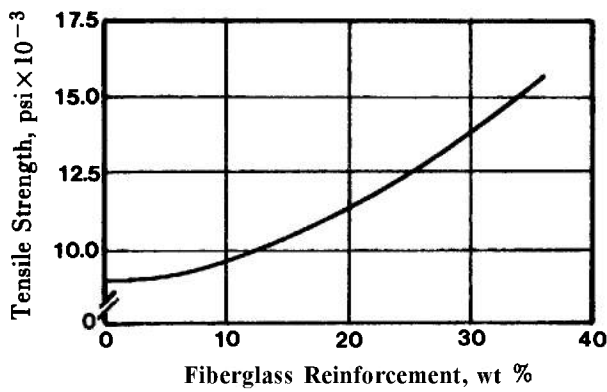


Figure 3-167. Tensile Strength vs Percent Fiberglass of Styrafil⁴⁴

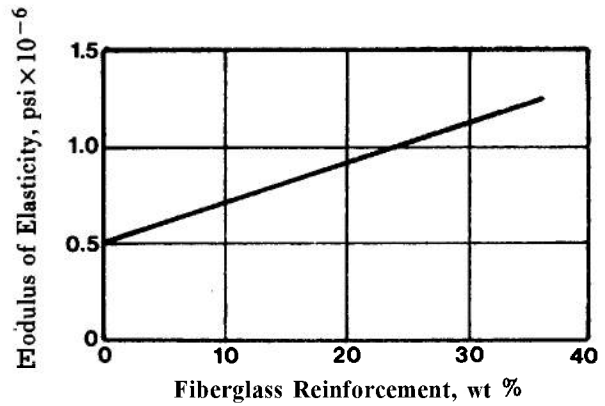


Figure 3-168. Modulus of Elasticity of Styrafil vs Glass Content⁴⁴

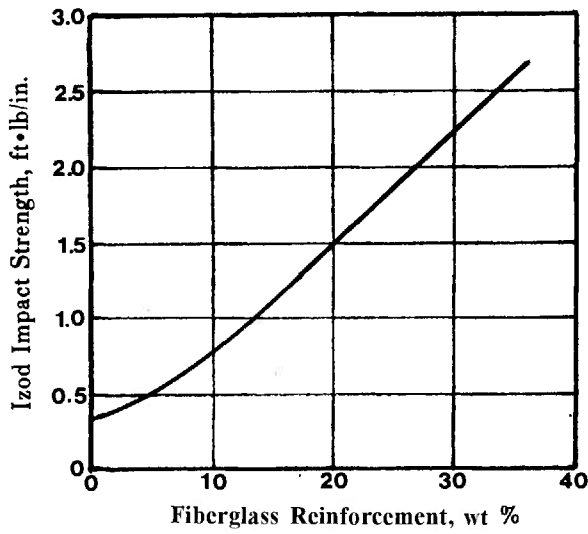


Figure 3-169. Izod Impact vs Glass Content of Styafil⁴⁴

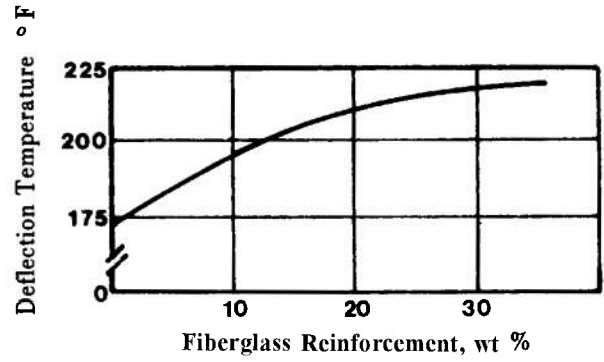
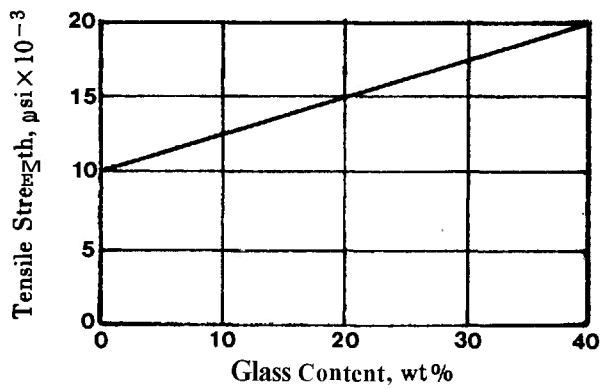
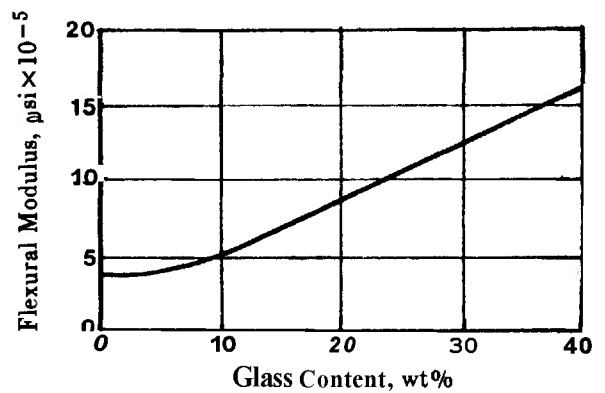


Figure 3-170. Deflection Temperature Under Load vs Glass Content for Styafil⁴⁴



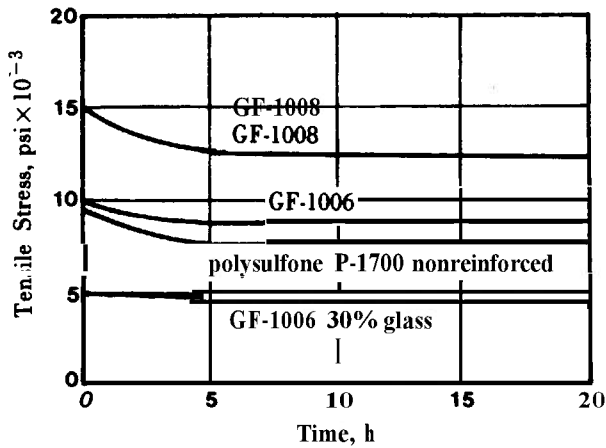
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Figure 3-171. Tensile Strength vs % Glass Content of Polysulfone⁴⁵



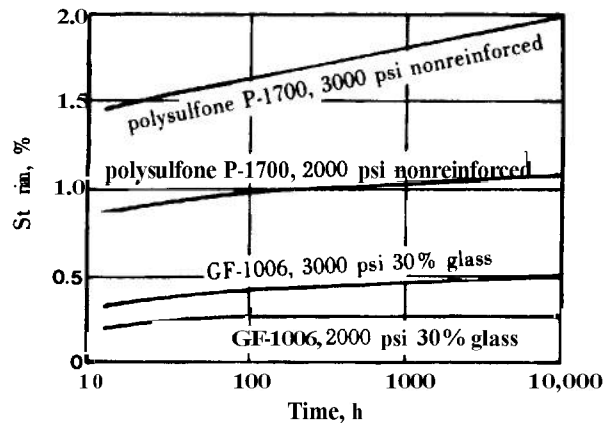
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Figure 3-172. Flexural Modulus vs % Glass Content of Polysulfone⁴⁵



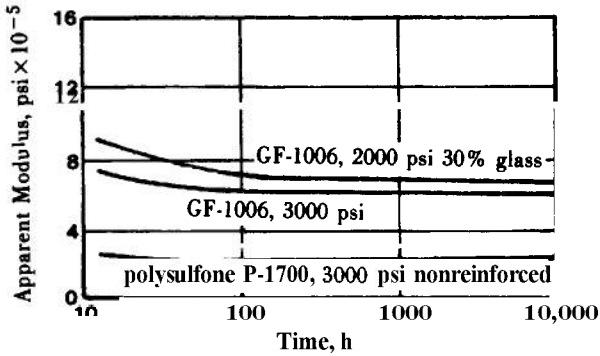
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Figure 3-173. Tensile Stress Relaxation, GF-1006 of Polysulfone⁴⁵



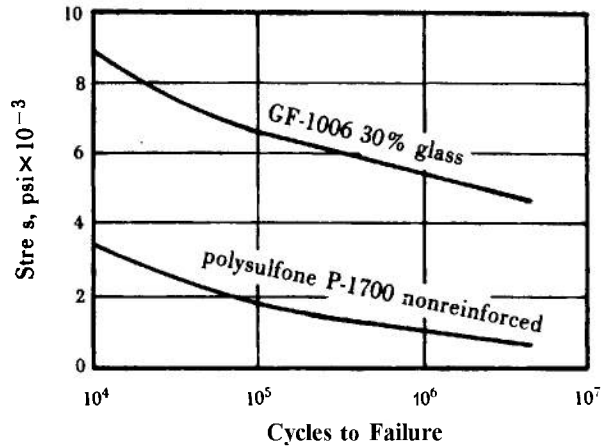
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Figure 3-174. Tensile Creep at 210° F of Polysulfone⁴⁵



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Figure 3-175. Tensile Creep Modulus vs Time at 210° F of Polysulfone⁴⁵



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Figure 3-176. Alternating Flexural Stress vs Cycles to Failure, GF-1006 Polysulfone⁴⁵

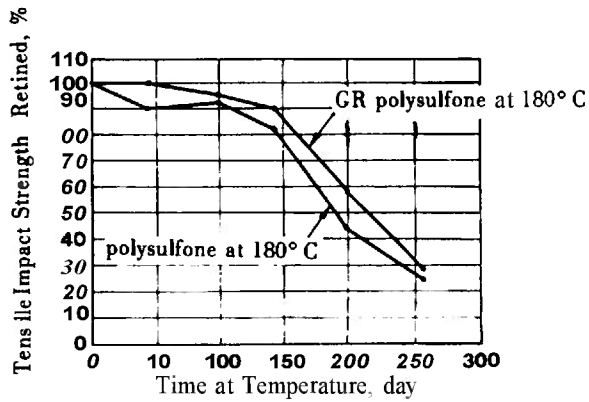


Figure 3-177. Percent Tensile Impact Strength vs Time at 180°C, Polysulfone²³

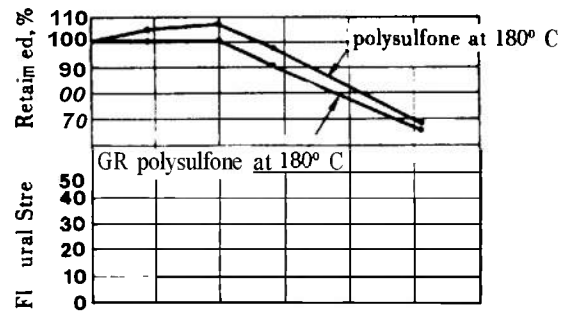
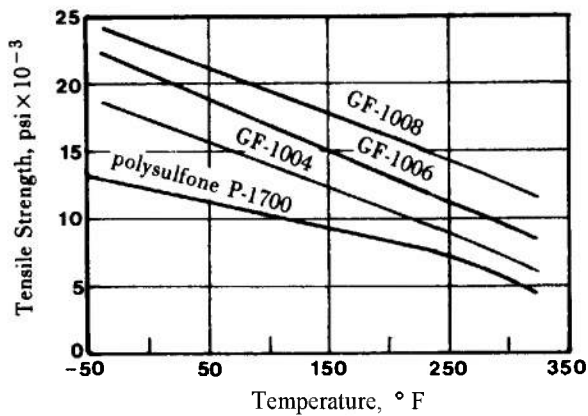
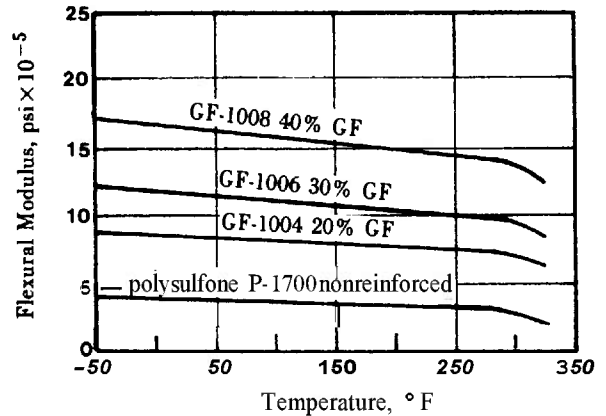


Figure 3-178. Percent Flexural Strength vs Time at 180°C, Polysulfone²³



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Figure 3-179. Tensile Strength vs Temperature of Glass-Reinforced Polysulfone⁴⁵



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Figure 3-180. Flexural Modulus vs Temperature of Glass-Reinforced Polysulfone⁴⁵

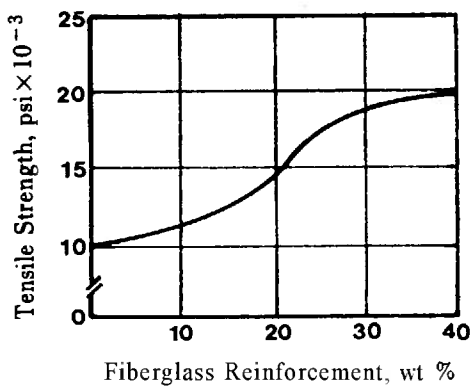


Figure 3-181. Tensile Strength vs Glass Content for Acrylafil⁴⁷

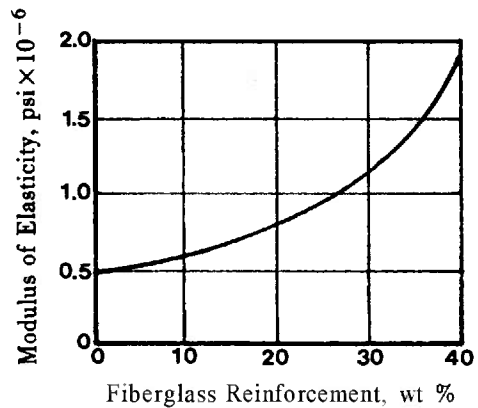


Figure 3-182. Modulus of Elasticity vs Glass Content for Acrylafil⁴⁷

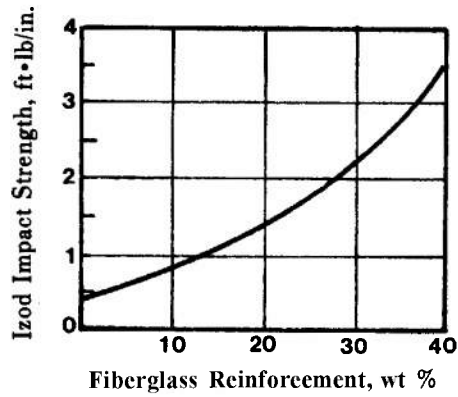


Figure 3-183. Izod Impact vs Glass Content for Acrylafil⁴⁷

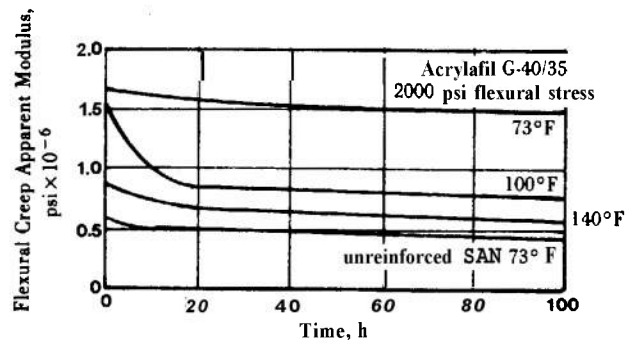


Figure 3-184. Flexural Creep - Apparent Modulus vs Time for Acrylafil⁴⁷

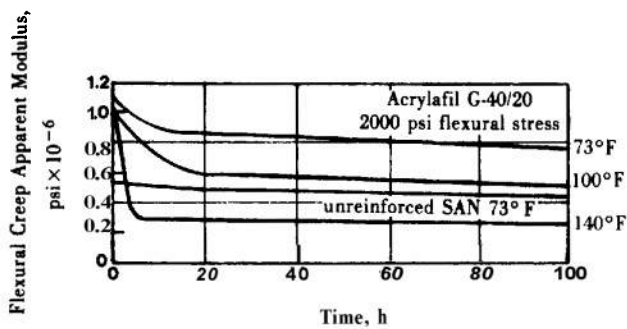


Figure 3-185. Flexural Creep - Apparent Modulus vs Time for Acrylafil⁴⁷

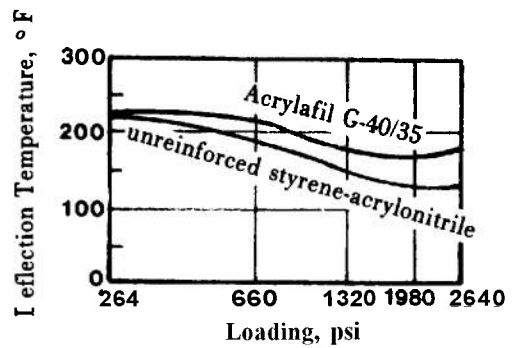


Figure 3-186. Deflection Temperature vs Loading for Acrylafil⁴⁷

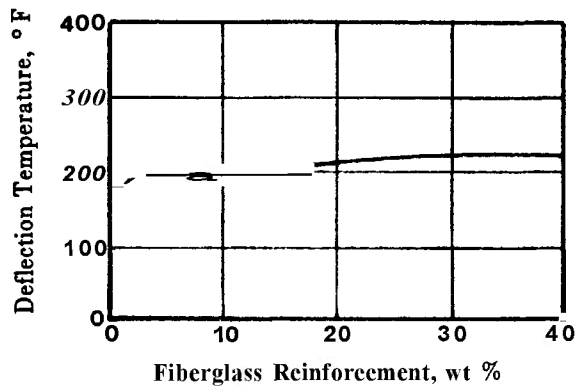


Figure 3-187. Deflection Temperature Under Load for Acrylafil vs Percent Fiberglass⁴⁷

TABLE 3-1. COMPARISON OF THE PHYSICAL AND MECHANICAL PROPERTIES OF GLASS-REINFORCED THERMOPLASTICS

Base Polymer	Glass Fiber Content, wt %	Property	Specific Gravity	Water Absorption, 24 h, %	Mold Shrinkage, in./in. or cm/cm	Tensile Yield Strength, psi	Elongation %	Tensile Modulus, psi X 10 ⁵	Flexural Strength, psi	Flexural Modulus, psi X 10 ³	Compressive Strength, psi	Shear Strength, psi	Izod Impact Strength, Notched/Unnotched, ft•lb/in.	Tensile Impact Strength, ft•lb/in. ²	Hardness
			D792	D570	D955	D638	D638	D790	D790	D695	D732	D256	D1322	D785, D2240	
Acetal (Copolymer)	0		1.41	0.22	0.0180	8,800	60	4.10	13,000	375	4,500	7,700	1.3/>40.0	—	M78
Acetal	10		1.47	0.24	0.008–0.01	12,500	6.0	—	18,500	550	—	8,000	1.4110.0	—	M82
Acetal	20		1.55	0.45	0.004	11,000	2.3	10.0	15,000	800	12,000	8,000	2.51—	—	M75–85
Acetal	30, 15TFE		1.75	0.20	0.0045	12,500	—	—	—	1,400	—	7,300	0.714	—	M86
Acetal (Chem. coupled)	30		1.63	0.30	0.003–0.016	19,500	3–4	—	29,000	1,400	—	9,000	1.8/8–10	—	M86
Acetal	30		1.63	0.60	0.005	13,000	2.0	—	17,500	1,300	11,500	8,200	0.8/3–4	—	M86
Acetal	40		1.71	0.85	0.004	21,500	—	—	—	1,800	11,000	—	1.4/8–9	—	M87
Acrylic	0		1.17	—	—	7,000–11,000	20–10	—	13,000–19,000	460	—	—	0.3–0.51—	—	M85–M105
Acrylic	20		1.33	—	—	15,000	2–3	—	19,000	950	—	—	1.3/3–4	—	—
ABS	0		1.05	0.45	0.004–0.009	7,500	5.0–2.50	3.0–4.5	13,000	3.0–4.6	12,500	—	2.0–6.0/—	—	R107–115
ABS	10		1.14	0.3	0.003–0.004	10,000	2.0	6.5	14,000	6.0	12,000	6,000	0.91—	—	M55–65
ABS	20		1.23	0.21	0.001	13,000	2.0	8.0	20,000	8.0	14,000	8,000	2.01—	—	M75–85
ABS	30		1.28	0.14	0.001	14,500	3–4	—	18,500	1,100	14,500	7,500	1.4/6–7	—	M99, R124
ABS	40		1.38	0.10	0.001	16,000	2–3	—	20,000	1,400	16,000	8,000	1.3/5–6	—	M102, R124
Fluoropolymers ETFE	0		1.7	0.029	0.030–0.040	6,500	100–400	1.2	—	200	7,100	—	No break/—	—	R50
ETFE	25		—	—	—	—	—	—	—	1,050	—	—	7.5/17–18	—	R74
ETFE	30		1.89	0.018	0.0025	14,000	—	—	—	—	—	—	—	—	—
FEP	0		2.12	<0.01	0.03–0.06	2,700–3,100	250–330	0.5	4,000	355	2,200	—	No break/—	—	D50
FEP FC 905	25		—	—	—	3,000	—	—	—	—	—	—	0.3/1–2	—	—
Nylon 6	0		1.15	1.8	0.013–0.016	11,800	80	2.7	15,000	400	8,800	9,600	1.01—	—	R119
Nylon 6	10		1.21	1.4	0.006–0.01	13,500	3–4	—	17,000	650	16,000	9,700	1.0/5–6	—	R118
Nylon 6	20		1.28	1.3	0.0045–0.0065	18,500	3–4	9.8	28,500	850	22,000	10,000	1.4/11–12	—	R119
Nylon 6	30, 15TFE		1.49	0.85	0.0035	19,000	—	—	—	1,250	—	8,600	1.9118	—	—
Nylon 6 (flame retardant)	30		1.58	0.85	0.003	22,000	—	—	33,000	1,250	—	—	1.5116	—	—
Nylon-Type 6	30		1.37	1.1	0.0035	23,000	3–4	—	34,000	1,200	23,000	12,000	2.3120	90.0	M92, R121
Nylon-Type 6	40		1.46	1.0	0.002–0.003	25,000	2.0	14.0	31,000	1,300	23,000	—	2.5116.0	—	R120
Nylon-Type 6	50		1.57	0.80	0.0025	31,000	2–3	13.0	45,000	2,000	24,000	13,000	4.0120	—	M98, R121
Nylon 616	0		1.15	1.5	0.015	11,800	60	4.0	15,000	410	4,900 (1%)	9,600	0.91—	—	R118
Nylon 616	10		1.21	1.1	0.006–0.015	14,000	3–4	—	20,000	650	18,000	10,000	0.8/5–6	—	R121
Nylon 6/6	20		1.28	0.9	0.005–0.006	19,000	3–4	12.0	29,000	850	23,000	10,600	1.2/8–9	—	R121
Nylon 616	30		1.37	0.9	0.004	26,000	2.0	15.0	38,000	1,300	22,500	—	2.0117	85.0	M96, R121
Nylon 616	30, 15TFE		1.49	0.50	0.0045	23,500	—	—	32,000	1,350	—	9,700	1.8116.0	—	—
Nylon 616 (flame retardant)	30		1.62	0.60	0.004	22,500	—	—	33,000	1,450	—	—	1.3111	—	—
Nylon 616	40		1.46	0.7	0.005–0.7	32,000	2.0	19.0	40,000	1,700	23,000	—	2.6115.0	—	R120
Nylon 6/6	50		1.57	0.50	0.003	32,000	—	—	—	2,220	—	—	3.3120	—	M100, R121
Nylon 616	60		1.70	0.40	0.003	33,000	—	—	50,000	2,800	—	13,800	3.3120	—	—

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TABLE 3-1. (cont'd)

Base Polymer	Glass Fiber Content, wt%	Property	Specific Gravity	Water Absorption, 24 h, %	Mold Shrinkage, in./in. or cm/cm	Tensile Yield Strength, psi	Elongation %	Tensile Modulus, psi x 10 ⁵	Flexural Strength, psi	Flexural Modulus, psi x 10 ³	Compressive Strength, psi	Shear Strength, psi	Izod Impact Strength, Notched/Unnotched, ft•lb/in.	Tensile Impact Strength, ft•lb/in. ²	Hardness
				D570	D955	D638		D638	D790	D790	D695	D732	D256	D1322	
Nylon 6110	0		1.09	0.40	0.013-0.016	8,500	85	—	12,000	280	3,000 (1%)	8,400	0.61—	—	R111
Nylon 6110	20		1.22	0.22	0.0040-0.0050	18,000	3-4	—	26,000	900	17,000	9,400	1.1/12-13	—	R119
Nylon 6/10 (flame retardant)	30		1.58	0.22	0.004	18,500	—	—	30,000	1,200	—	—	1.5/14	—	—
Nylon 6/10	30		1.30	0.20	0.0035	21,000	—	—	—	1,100	—	—	2.4/22	100.0	M93, R120
Nylon 6/10	30, 15TFE		1.46	0.15	0.0035	20,000	—	—	—	1,150	—	8,400	2.2/20	—	—
Nylon 6/10	50		1.50	0.16	0.0025	29,000	—	—	—	1,900	—	—	4.5/20	—	M99, R122
Nylon 6112	0		1.08	—	0.0015	8,800	100	—	—	290	—	—	0.85/—	—	—
Nylon 6/12	25		1.25	0.22	—	20,000	5-6	—	28,000	1,000	27,000	10,000	2.0/13	—	R119
Nylon 6/12	30, 15TFE		1.43	0.15	0.0035	21,000	—	—	—	1,150	—	8,500	2.0/13	—	—
Nylon 6/12	30		1.30	0.21	0.0035	22,000	—	—	—	1,150	—	—	2.5/14	—	M93, R120
Nylon 6/12	50		1.50	0.16	0.0025	28,500	—	—	—	1,900	—	—	4.0/15	—	M99, R122
Nylon 11	0		1.05	—	0.012	8,000	300	1.85	—	1,700	—	—	1.8/—	—	R108
Nylon 11	30		1.24	—	—	14,000	3-4	—	20,000	875	—	—	2.2/7-8	—	—
Nylon 12	0		1.02	0.25	0.015	9,250	300	1.8	—	165	—	—	5.5/—	—	R109
Nylon 12	30		1.23	0.07	0.003	17,400	5.0	—	22,300	1,000	—	—	3.0/—	—	R109
Polycarbonate	0		1.20	0.15	0.0070	9,500	100	3.45	13,500	340	12,500	8,500	2.7/>60.0	—	M70
Polycarbonate	20		1.34	0.09	0.0030	16,000	2.5	12.0	25,000	850	18,000	8,600	3.4/17.0	—	R118
Polycarbonate	30, 15TFE		1.55	0.06	0.0015	17,500	—	—	—	1,200	—	7,500	2.0/12	—	—
Polycarbonate	30		1.43	0.07	0.001	18,500	2.0	14.0	28,000	1,200	20,000	9,400	3.7/17-18	—	M95, R118
Polycarbonate	40		1.52	0.06	0.001	21,000	2.0	17.0	30,000	1,500	22,000	9,900	4.0/18	—	M97, R118
Polyester	0		1.31	—	0.0015	8,200	50-300	2.8	12,000-16,700	400	—	—	0.81/—	—	M78
Polyester	10		1.37	—	—	11,200	5	—	—	—	—	—	0.6/—	—	—
Polyester	20		1.43	0.08	0.0035-0.0055	17,500	4-5	—	24,000	1,100	17,000	—	1.2/6-7	—	R118
Polyester	30, 15TFE		1.60	0.04	0.0045	16,500	—	—	—	1,250	—	8,000	1.37/—	—	—
Polyester	30		1.52	0.06	0.003	19,500	—	—	—	1,350	—	—	1.6-1.8/9-10	38.0	M84, R119
Polyester	40		1.62	0.04	0.003	22,000	—	—	—	1,600	—	—	2.0/11-12	—	M86, R120
Polyether Sulfone	0		1.37	0.43	0.007	12,200	—	—	18,700	370	—	—	1.6/—	—	M88
Polyether Sulfone	20		1.51	0.37	0.003	18,000	3-4	—	25,700	—	—	—	1.4/8.0	40.0	M98
Polyether Sulfone	30		1.60	0.35	0.002-0.003	19,000	—	—	—	1,200	—	—	1.5/10	—	M98
Polyether Sulfone	40		1.68	0.31	0.0015	22,000	3-4	—	30,000	1,600	—	—	1.6/12	60	M98
Polyethylene	0		0.941	0.01	0.02-0.05	3,100-5,500	20-1,300	0.6-1.8	—	100-260	2,700-3,600	—	0.5-20.0/—	—	070
			0.965	0.01	0.02-0.04	4,200	250	1.2	4,000	200	3,200	—	No break/—	—	R10
Polyethylene	20		1.10	0.010	0.0035-0.0045	8,000	2-3	—	10,000	600	—	4,000	1.0/4-5	—	R80
Polyethylene	30		1.17	0.015	0.0030	10,000	2-3	—	11,500	900	—	4,400	1.1/8.9	63.0	R85
Polyethylene	40		1.28	0.02	0.0025-0.0035	11,500	2-3	—	14,000	1,100	—	4,900	1.3/11-12	—	R90

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TABLE 3-1. (cont'd)

Base Polymer	Glass Fiber Content, wt %	Property	Specific Gravity	Water Absorption, 24 h, %	Mold Shrinkage, in./in. or cm/cm	Tensile Yield Strength, psi	Elongation %	Tensile Modulus, psi x 10 ⁵	Flexural Strength, psi	Flexural Modulus, psi x 10 ³	Compressive Strength, psi	Shear Strength, psi	Izod impact Strength, Notched/Unnotched, ft•lb/in.	Tensile Impact Strength, ft•lb/in. ²	Hardness
		ASTM	D792	D570	D955	D638	D638	D790	D790	3695	D732	D256	D1322	D785, D2240	
Polyphenylene Oxide (modified)	0		1.06	0.066	0.005–0.007	9,600	60	3.55	13,500	360	16,400	10,500	–	170	R119
Polyphenylene Oxide (modified)	20		1.21	0.06	0.002–0.004	14,500	4–6	9.20	18,500	750	17,600	10,400	–	60	1106
Polyphenylene Oxide (modified)	30		1.27	0.06	0.001–0.003	17,000	4–6	12.0	20,000	1,100	17,900	10,600	–	50	1108
Polyphenylene Oxide (modified) flame retardant	30		1.27	0.05	0.0015	15,700	–	–	20,000	1,200	–	–	–	–	–
Polyphenylene Oxide	40		1.38	0.06	0.001	22,000	–	–	–	1,350	–	–	1.7/7–8	–	M94
Polyphenylene Sulfide	0		1.34	0.20	0.010	10,800	3–4	6.3	20,000	600	16,000	–	0.3/3–4	–	R124
Polyphenylene Sulfide	30, 15TFE		1.69	0.03	0.001	19,000	1.0	17.0	25,000	1,300	15,000	7,100	1.1/6–7	–	R118
Polyphenylene Sulfide	30		1.56	0.04	0.002	20,000	1.3	16.0	28,000	1,600	24,000	–	1.4/8–9	–	R121
Polyphenylene Sulfide	40		1.68	0.02	0.001	23,000	1.3	20.0	30,000	1,800	25,000	–	1.5/11–12	–	R123
Polypropylene	0		0.902	<0.01	0.025	5,000	200–700	2.25	8,000	–	–	–	0.5–2.2/–	–	R110
Polypropylene	20		1.04	0.01	0.004–0.0045	9,100	2–3	0.56	11,000	600	7,700	–	1.4/6–7	–	M49
Polypropylene (flame retardant)	20		1.31	0.02	0.004	6,000	–	–	–	750	–	–	–	–	–
Polypropylene	30, 15TFE		1.25	0.02	0.004	9,700	–	–	–	1,000	–	5,200	1.1/3	–	–
Polypropylene	30		1.13	0.03	0.004	9,800	2–3	0.85	12,000	800	8,500	–	1.6/5–6	28.0	M57, R111
Polypropylene	40		1.22	0.06	0.0035	10,500	1–2	10.5	12,500	1,000	9,800	–	1.8/4–5	–	M59, R111
Polystyrene	0		1.04–1.09	<1.5	0.002–0.006	5,000–10,000	1.0–2.5	400–600	8,000–14,000	400	11,500–16,000	–	0.25/–	–	M80
Polystyrene	20		1.20	0.07	0.0010–0.0020	1,500	2–3	10.5	15,000	950	16,700	–	0.9/2–3	–	M90
Polystyrene	30		1.28	0.05	0.0005–0.001	3,500	2–3	13.0	16,200	1,300	17,300	–	1.0/2.3	19.0	M92
Polystyrene	40		1.38	0.05	0.0005–0.001	6,000	2–3	16.5	17,500	1,500	17,800	–	1.2/2–3	–	M93
Polysulfone	0		1.24	0.20	0.0070	0,200	75	3.60	15,400	390	14,000	9,000	1.2/> 60.0	–	M69
Polysulfone	10		1.38	0.20	0.0035	5,000	–	–	21,000	850	–	9,000	1.3/12.0	–	–
Polysulfone	30		1.45	0.20	0.002–0.003	8,000	2.1	12.0	24,000	1,200	22,000	9,500	1.8/14	63.0	M92, L108
Polysulfone	40		1.55	0.18	0.002	0,000	1.7	17.0	27,000	1,600	24,000	10,000	2.0/16	–	M92, L109
Polysulfone	30, 15TFE		1.59	0.10	0.0020	15,500	–	–	22,500	–	–	7,500	1.6/8.0	–	–
Polyurethane	0		1.25	0.3	0.008–0.012	4,500–8,400	100–650	0.1–3.5	8,000–9,000	50.0	4,000	–	No break/–	–	077
Polyurethane	20		1.37	0.15	0.005	14,000	3.3	8.0	19,000	620	10,000	–	1.5/11.0	–	085
Polyurethane	30, 15TFE		1.59	0.15	0.0035	7,800	–	–	–	–	–	–	–	–	–
Polyurethane	30		1.46	0.15	0.004	17,000	3.5	10.5	23,000	800	12,000	–	2.0/11.5	–	D86
Polyurethane	40		1.55	0.15	0.003	19,000	3.8	13.0	25,000	1,000	13,000	–	3.0/12.4	–	086
Polyvinyl Chloride	0		1.30	–	0.001–0.005	6,000–7,500	40–80	3.5–6.0	10,000–16,000	300–500	8,000–13,000	–	0.4–20/–	–	D65–85
Polyvinyl Chloride	15		1.54	0.01	0.001	13,000	2–3	10.0	18,000	850	12,000	7,000	1.2/6.5	35.0 (25% GR)	R115

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TABLE 3.1 (cont'd)

Base Polymer	Glass Fiber Content, wt %	Property	Specific Gravity	Water Absorption, 24 h, %	Mold Shrinkage, in./in. or cm/cm	Tensile Yield Strength, psi	Elongation %	Tensile Modulus, psi x 10 ⁵	Flexural Strength, psi	Flexural Modulus, psi x 10 ³	Compressive Strength, psi	Shear Strength, psi	Izod Impact Strength, Notched/Unnotched, ft•lb/in.	Tensile Impact Strength, ft•lb/in. ²	Hardness
		ASTM	D 792	D 570	D 955	D 638		0638	D 790	0790	D 695	D 732	D 256	D 1322	0785, 02240
SAN	0		1.03	—	—	11,000	5	9.7–17.5	5,000	—	—	—	0.04/—	—	M80
SAN	20		1.22	0.15	0.0010–0.0020	15,800	2–3	11.5	19,800	1,100	19,400	9,000	1.0/3–4	—	R122
SAN	30, 15TFE		1.43	0.09	0.0015	12,800	—	—	—	1,500	—	8,200	0.8/3	—	—
SAN (flame retardant)	30		1.50	0.05	0.001	14,200	—	—	—	1,600	—	—	—	—	—
SAN	30		1.31	0.10	0.0005–0.001	17,400	2–3	16.0	22,000	1,500	21,000	9,400	1.0/3–4	30.0	M94, R 123
SAN	40		1.40	0.08	0.0005–0.001	18,600	2–3	19.5	23,200	1,850	23,200	9,800	1.1/3–4	—	M97, R123

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TABLE 3-2. ULTIMATE TENSILE STRESS OF GLASS-REINFORCED THERMOPLASTICS AS A FUNCTION OF LOADING SPEED'

Base Resin	Glass Content, wt %	Ultimate Tensile Stress, psi			
		0.05 in./min	1.0 in./min	400 in./min	8,000 in./min
SAN	35	17,900	18,200	19,800	23,200
Polystyrene	30	12,000	13,000	15,100	17,100
Polycarbonate	40	21,000	23,000	27,400	34,400
Polycarbonate ^a	40	20,900	22,800	26,700	—
Polyethylene	30	10,800	12,500	15,100	—
Polysulfone	30	18,000	19,500	23,300	—
Polypropylene	30	7,600	8,000	11,200	—
Nylon 6	30	21,000	23,000	29,800	—
Nylon 6 ^a	30	21,200	23,200	27,300	—
Nylon 6/10	30	21,000	23,000	32,800	—
Nylon 6/6	30	24,200	26,500	32,800	35,900
Nylon 6/6 ^a	30	24,700	27,100	33,500	—
Polyurethane	40	9,400	11,800	18,900	—
PVC	25	15,800	17,000	25,500	—
Polyester	30	19,400	19,800	30,600	—

All glass-reinforced nylon resin specimens are dry, as molded.

^aLong glass reinforced

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TABLE 3-3. HYDROLYSIS RESISTANCE OF GLASS-REINFORCED THERMOPLASTICS'

Base Resin	Glass Filler, wt %	Glass Filler, vol %	Water Absorption at 23°C, % (ASTM D570)		Water Absorption at 100°C, %		
			24 h	Saturation	100 h	1,000 h	5,000 h
			SAN	30.00	15.40	0.10	0.32
Polycarbonate	30.00	16.84	0.07	0.18	0.32	0.52	1.02
Polysulfone	30.00	17.30	0.20	0.58	0.43	0.69	0.80
Polyacetal	30.00	19.21	0.25	1.15	0.50	1.07	1.73
Polypropylene	30.00	13.20	0.03	0.06	0.45	0.97	1.23
PPO	30.00	15.27	0.06	0.12	0.08	0.20	0.33
Nylon 6/10	30.00	15.41	0.20	1.85	2.16	2.62	5.40
Modified PPO	30.00	15.27	0.06	0.11	0.13	0.29	0.40
PVC	25.00	15.15	0.02	0.12	1.24	4.12	5.41

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TABLE 3-4. TENSILE PROPERTY CHANGES OF GLASS-REINFORCED PLASTICS AFTER 100°C WATER AGING²

Basic Resin	Glass Filler, wt %	Glass Filler, vol %	Tensile Strength During Water Aging at 100°C, psi					
			Initial	100 h	1,000 h	5,000 h	10,000 h	15,000 h
SAN	30.00	15.40	16,700	9,500	6,000	3,000	—	—
Polycarbonate	30.00	16.80	19,800	10,000	5,600	4,000	—	—
Polycarbonate	0.00	0.00	8,800	9,700	5,600	4,000	—	—
Polysulfone	30.00	7.50	17,100	12,000	12,200	12,600	12,800	12,900
Polysulfone	0.00	0.00	10,500	10,900	11,900	12,500	—	—
Polyacetal	30.00	9.20	14,100	10,000	8,000	2,500	—	—
Polyacetal	0.00	0.00	9,500	9,800	9,300	2,000	—	—
Polypropylene	30.00	3.20	7,600	7,000	6,600	6,200	6,000	5,850
PPO	30.00	5.20	14,900	12,800	11,800	11,500	11,000	10,000
Nylon 6/10	30.00	15.40	20,000	9,500	8,300	6,000	4,500	—
PVC	25.00	15.10	17,400	11,500	8,600	6,700	5,000	—
Modified PPO	30.00	15.20	21,500	18,000	14,000	14,000	13,500	5,000
Modified PPO	0.00	0.00	8,600	8,900	8,600	8,300	4,500	—

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TABLE 3-5. ROCKWELL HARDNESS SCALES

Scale	Major Load, kg	Indenter Diameter, in.
M	100	0.2500
L	60	0.2500
R	60	0.5000

TABLE 3-6. APPARENT CREEP MODULUS OF GLASS-REINFORCED THERMOPLASTICS¹

MATERIAL (thermoplastics)				SPECIMEN ²			CREEP TEST CONDITIONS ²				CREEP TEST DATA ²									
Plastic	Trade Name ¹ and Grade Designation	Grade Description	ASTM, Military, or Other Specification Classification	Molding Method	Type or Shape	Dimensions	Type of Load	Strain Measure	Special Specimen Conditioning	Test temp., °F	Initial ³ Applied Stress, psi	Creep (apparent) Modulus, ⁵ ksi						Time at Latest Test Point, h	Time at Rupture ⁶ or Onset of Yielding at Initial Applied Stress in Air, h	
												Calculated from total creep strain or deflection (before rupture and onset of yielding) at the following test times:								
												1 h	10 h	30 h	100 h	300 h	1000 h			at latest test point
ABS	Cycloc DFA	Inj. molding medium imp. high gloss	Fed. spec. L-P-1183 Type 2	IM	RB	4	F2	3		73	1000	345	323	313	278	244	215			
											2000	345	323	308	274	243	211			
											120	1000	303	222	187	154	125			94
			140	1000	137	93	8	63	53	44										
	Cycloc GSE	Extrusion high imp. high modulus	Fed. Spec. L-P-1183 Types 2, 5 and 6	IM	RB	4	F2	3		73	1000	294	286	278	256	238	208			
											2000	294	286	278	256	233	204			
											120	1000	238	182	158	133	115			100
			140	1000	279	122	100	83	71	60										
			160	1000	105	59	49	41	36	32										
	Cycloc LS	Extrusion, high-imp. thermoforming	Fed. Spec. L-P-1183	IM	RB	4	F2	3		73	1000	22w	227	204	200	189	157			
											2000	224	211	200	189	179	155			
											120	1000	169	135	118	98	83			71
		140	1000	159	121	103	86	74	63											
		160	1000	133	87	72	61	51	43											
Cycloy KHS	ABS/polycarbonate blend, extrusion, high imp., flame-ret., heat res., high modulus			ES	RB	4	F2	3		73	2000	343	328	323	308	300	256			
											3000	341	326	323	308	300	256			
											120	2000	303	263	249	222	206			182
											3000	303	270	248	222	208	188			
											140	2000	244	206	189	174	160			146
		3000	250	207	188	169	155	143												
		160	2000	217	182	144	127	114	102											
		3000	217	163	143	126	112	101												
Kralastic W	Pipe extrusion	Fed. Spec. L-P-1183 Types 2, 5, and 6	CM	T1	1	T	1		73	2000	230	220	211	200		194	167			
										2500	223	208	195	180		172	167			
										3000	211	185	165	130		12A	111			
					RS	2	T	1		73	1500	230	224	217	211	200	188	140	50,000	
Kralastic MH	Easy flow, injection molding	Fed. Spec. L-P-1183 Types 1 and 2	CM	T1	1	T	1		73	1500	284	278	273	263	254	240				
										2000	284	268	260	245	230	211				
										2500										
										3000	254	224	203	170	133				125	390
										3500	233	165							146	17
		4000	167																	
Kralastic MV	Sheet extrusion, injection molding	Fed. Spec. L-P-1183 Types 2, 5, and 6	CM	T1	1	T	1		73	2000	216	196	181	161	140					
										2500	202	172	152					132	83	
										3000	181	136								
		140	500	161	132	109	77	49												
		1000	171	136	114	76	44													
		1500	168	127	99															

²See p. 3-107 for explanatory notes

(continued)

TABLE 3-6 (cont'd)

MATERIAL (thermoplastics)				TEST SPECIMEN ^a			CREEP TEST CONDITIONS ^a				CREEP TEST DATA ^a										
Plastic	Trade Name ¹ and Grade Designation	Grade Description	ASTM, Military, or Other Specification Classification	Molding Method	Type or Shape	Dimensions	Type of Load	Strain Measure	Special Specimen Conditioning	Test Temp., °F	Initial ³ Applied Stress, psi	Creep (apparent) Modulus, ⁵ ksi							Time at latest Test Point, h	Time at Rupture ⁶ or Onset of Yielding at Initial Applied Stress in Air, h	
												Calculated from total creep strain or deflection (before rupture and onset of yielding) at the following test times:									at latest test point
												1 h	10 h	30 h	100 h	300 h	1000 h				
Acetal	Hostaform C9021 Creep data also apply to Hostaform C14021, C27021, Hostaform C2520	Copolymer, x-p, inj. molding Low visc. inj. molding High visc., extrusion and inj. molding		IM	RB	21	F7	3		68	1422	356	312	270	256	241	227	185	50,000		
											122	1422	241	185	178	156	149	142	135		50,000
											176	1422	163	135	128	121	114	112	111		50,000
											212	1422	114	106	102	99		99	200		
	Kematal M90 Creep data also apply to Kematal M25 Kematal M270	Copolymer, x-p, inj. molding High visc. extrusion, inj. molding Low visc. inj. molding		IM	M	RB	4	F2	3		73	500	380	340		310	300	270	135	60,000	
												5000	380	340		270	240	220	170	20,000	
												180	500	100	88		77		68	37	
	Delrin 570X	20% glass fiber-reinforced homopolymer, x-p, inj. molding		IM	RB	4	F4	3		73	500	1220	1100	920	800	700	640	380	20,000		
											1000	940	830	750	670	610	540	300	20,000		
											1500	880	750	720	620	580	500	380	10,000		
											2000	870	780	700	630	560	490	320	20,000		
											140	500	680	580	500	410	350	300	210		20,000
1800											530	460	400	350	310	280	260	20,000			
Celcon GC-25	25% glass-coupled copolymer, x-p, inj. molding		IM	RB	4	F2	3		180	500	535	-	450	410		380	190	20,000			
										3120	535	-	450	410		370	330	1200			
										240	500	325	-	260	236		186	162		5000	
										180	500	535	-	450	410		380	190		20,000	
										3120	535	-	450	410		370	330	1200			
										240	500	325	-	260	236		186	162		5000	
Formaldafil	20% glass fiber-reinforced, x-p, injection molding	MIL-P-46137(MR)	IM	RB	11	F2	3		73	4000	700	640	580	540							
										100	4000	480	380	360	340						
										180	4000	350	190	150	120						
Hostaform C9021 CV 1/2	30% glass fiber-reinforced copolymer, x-p, inj. molding		IM	RB	21	F7	3		68	1422	1190	1100	1065	1020	994	958	936	2200			
										176	1422	900	823	795	738	710	638	595		2200	
Thermocomp KFL 4036	30% glass fiber-reinforced, 15% PTFE lub., inj. molding		IM	RB	4	F4	3		75	2000	-	1150	950	850	800	790					

^aSee p. 3-107 for explanatory notes

(continued)

TABLE 3-6 (cont'd)

MATERIAL (thermoplastics ¹)				TEST SPECIMEN ²			CREEP TEST CONDITIONS ²				CREEP TEST DATA ²									
Plastic	Trade Name ¹ and Grade Designation	Grade Description	ASTM, Military, or Other Specification Classification	Molding Method	Type or Shape	Dimensions	Type of Load	Strain Measure	Special Specimen Conditioning	Test temp., °F	Initial ³ Applied Stress, psi	Creep (apparent) Modulus, 5 ksi							Time at Latest Test Point, h	Time at Rupture ⁶ or Onset of Yielding at Initial Applied Stress in Air, h
												Calculated from total creep strain or deflection (before rupture and onset of yielding) at the following test times:								
												1 h	10 h	30 h	100 h	300 h	1000 h	at latest test point		
Nylon	Akulon B2 N 957	Nylon 6, high-impact; inj. molding	ASTM D 789 Type II, Grade 1	IM	I2	9	T	1	Dry	73	6000	350	300	270	240	210				
									Equilb. with 50% RH ¹⁰	73	1000	76	68	64	60	55	48			
	Fosta 1016	Nylon 6 high mod; inj. molding		IM	1B	1	T	1	Equilb. with 50% RH ¹⁰	73	2500	180	150	130	110	90	80			
	Grlon AZ801M	Nylon 6, inj. molding	ASTM D 789 Type II, Grade 2	IM	T1	1	T1	1	Dry	176	710	125	110	105	95	90	85	75	5000	
									Equilb. with 20% RH ¹⁰	77	710	145	135	130	127	123	126	115	5000	
									Equilb. with 30% RH ¹⁰	176	1400	55	51	49	47	46	44	43	5000	
									Equilb. with 50% RH ¹⁰	77	1400	120	110	102	96	90	86	79	5000	
									Max. moisture content ¹¹	77	1140	46	41	38	34	33	30	26	5000	
									176	574	37	34	33	31	29	28	26	5000		
	Nylon	Akulon R-800	Nylon 6/6, r.p., inj. molding	ASTM D 789 Type I, Grade 2	IM	F2	1	T	1	Dry	73	1500	420	395	360	340	290			
										Equilb. with 50% RH ¹⁰	73	1500	160	130	120	115	105	100		
		Zytel 101 Creep data also apply to Zytel 103 HS1 L, 121 and 122	Nylon 6/6, r.p., inj. molding Specially stabilized, inj. molding	ASTM D 789 Type I, Grade 2 MIL-M-20683A Type I	IM	RB	4	F4	1	Equilb. with 50% RH ¹⁰	73	1000	145	123	111	101	92	83	75	3000
										140	2000	127	103	92	82	71	64	57	3000	
										140	1000	84	75	71	67	62	58	54	3000	
									Max. moisture cont. ¹¹	73	1400	105	95	90	86	82	78	68	10,000	
										194	1400	75	70	68	65	62	60	55	10,000	
Zytel 109		Copolym., inj. molding	ASTM D 789 Type VII, Grade 2	IM	RB	4	F4	3	Dry (no conditioning) ⁹	194	1000	56	60	58	55	52	50	45	10,000	
									Equilb. with 50% RH ¹⁰	73	1000	95	90	85	80	75	71	65	10,000	
									Max. moisture cont. ¹¹	73	1000	77	71	68	65	63	61	57	10,000	
									194	1000	61	59	57	56	52	49	47	10,000		
Celanese 1000, 1310 Creep data also apply to Celanese 1200	Nylon 6/6, r.p., inj. molding	ASTM D 789 Type I, Grade 2			4	F4	3	Dry (no conditioning) ⁹	195	1400	91	81	80	75	75	71	65	10,000		
Moleculoy 66-01	Nylon 6/6, inj. molding	ASTM D 789 Type I, Grade 2	IM	RB	4	F4	3	Equilb. with 50% RH ¹⁰	73	1000	155	128	118	105	97	85	77	3000		
									2000	135	108	96	84	77	69	61	3000			

²See p. 3-107 for explanatory notes

(continued)

TABLE 3-6 (cont'd)

Zytel 131	Nylon 6/6, x p inj molding, nucleated, fast cycling, stiff	ASTM D 789 Type Ia, Grade 2	IM	RB	4	F4	3	Equilib. with 50% RH ¹⁰	73	2000	152	125	112	102	93	84	78	3000	
Zytel 408	Nylon 6/6 modified x p inj molding		IM	RB	4	F4	3	Equilib with 50% RH ¹⁰	73	1000	129	104	95	85	78	69	62	3000	
									2000	112	85	72	61	53	45	45	3000		
Celanese 1003	Nylon 6/6, heat stabilized, inj molding	ASTM D 789 Type I, Grade 2	IM	RB	4	F2	3	Dry (no conditioning) ¹¹	250	500	52	51	50	47	44	42	36	4800	
									300	500	36	36	35	34	32	30	29	670	
										1000	35	35	34	32	30			670	
Maranyl A 100	Nylon 6/6, inj molding		IM	TB	10	T	1A	Dry	73	1500	441	436	427	421	407				
Creep data also apply to Maranyl A101	Specially stab inj molding							Equilib with 50% RH ¹¹	73	1500	192	153	136	116	98	80			
Vydync 10V, 20M, 20V, 21, 21X, 21L	Nylon 6/6, x p inj molding	ASTM D 789 Type I, Grade 2	IM	RB	4	F4	3	Dry (no conditioning) ¹¹	73	2000							157		
Creep data also apply to Vydync 10H, 20H	Heat stab inj molding																		
Vydync M340	Nylon 6/6 modif VO Flame ret inj molding		IM	RB	4	F4	3	Conditioning ¹¹	73	2000							125		
Vydync 80X	Copolymer 6 6/6 inj molding		IM	RB	4	F4	3	Dry (no conditioning) ¹¹	73	2000							117		
Vydync 60H	Nylon 6/9 Extrusion		IM	RB	4	F4	3	Dry (no conditioning) ¹¹	73	2000							59		
Zytel 158	Nylon 6/12 x p inj molding	MIL-M 20693A Type III	IM	RB	4	F4	3	Equilib with 50% RH ¹⁰	73	2000	158	122	108	95	85	76	71	3000	
									140	2000	72	60	56	52					
Grlamid L20G	Nylon 12 inj molding		IM	T1	1	T	1	Dry	176	710	36	32	30	29	28	27	25	5000	
								Equilib with 20% RH ¹⁰	77	710	175	160	150	148	145	137	129	500	
								Equilib with 30% RH ¹⁰	176	1400	36	35	32	30	29	27	25	5000	
								Equilib with 50% RH ¹⁰	77	1400	120	97	86	78	69	62	53	5000	
								Max Moisture content ¹¹	176	285	31	28	28	27	26	25	24	5000	
Troxamid T	Clear, transparent, inj. molding		IM	T1	22	T		Dry-tested at 50% RH ¹¹	73	1000	350	319		265		197	88	10,000	
									2000	344	313		258		190	82	10,000		
									176	1000	285	256		218		166	98	10,000	
									2000	282	250		209		154	88	10,000		
Plaskon 8230	Nylon 6, 1% glass fiber-reinforced, inj. molding		IM	T2	8	T	1	Dry (no conditioning) ¹¹	73	2000	465	415	380	345			325	165	
									3000	460	405	370	320	270					
									4000	460	405	360	305	245			230	400	
									100	2000	215	171	153	129	109		102	400	
									4000	205	147	124	104	82			70	500	
									150	1000	131	114	107	95			93	200	
									2000	102	88	84	80				78	200	
									3000	93	74	66	60				58	200	
								Equilib with 50% RH ¹⁰	200	800	89	82	79	76			74	200	
									73	2000	168	140	127	118	108				
									3000	154	133	121	107						
									4000	92	77	68	58				93	250	
Plaskon 8231	Nylon 6, 4% glass fiber-reinforced, inj. molding		IM	T2	8	T	1	Equilib with 50% RH ¹⁰	73	2000	380	330	310	290	260	250	220	7500	
									4000	280	235	220	200	190	170	98		17,000	
Plaskon 8233	Nylon 6, 0% glass fiber-reinforced, inj. molding	Fed. Spec. LP 395 B Type 1	IM	T2	8	T	1	Dry (no conditioning) ¹¹	250	4000	270	250	230	210	200	180			
								Equilib. with 50% RH ¹⁰	73	4000	610	540	515	480	460	430	380		17,000

(continued)

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TABLE 3-6 (cont'd)

MATERIAL (thermoplastics ¹)				TEST SPECIMEN ^a			CREEP TEST CONDITIONS ^a				CREEP TEST DATA ^a											
Plastic	Trade Name ¹ and Grade Designation	Grade Description	ASTM, Military, or Other Specification Classification	Molding Method	Type or Shape	Dimensions	Type of Load	Strain Measure	Special Specimen Conditioning	Test temp., °F	Initial ² Applied Stress, psi	Creep (apparent) Modulus, ⁵ ksi						Time at latest Test Point, h	Time at Rupture ⁶ or Onset of Yielding at Initial Applied Stress in Air, h			
												Calculated from total creep strain or deflection (before rupture and onset of yielding) at the following test times:										
												1 h	10 h	30 h	100 h	300 h	1000 h			at latest test point		
Nylon	Akulon K2-82V	Nylon 6, 30% glass fiber reinforced, inj. molding		IM	T1	1	T	1	Dry	73	6000	850	820	780	730	660						
												Equilib. with 50% RH ¹⁰	73	2000 3000 4000	1350 1140 840	1160 950 700	1040 890 610	950 790 560	820 710 490	560 490 350		
	Grlon PV 3H	Nylon 6, 30% glass fiber reinforced, inj. molding		IM	T1	1	T	1	Equilib. with 65% RH ¹⁰	68	1000 2000 4000	960 820 990	870	820	770	720	690	640	590	10,000		
													140	1000 2000 4000	480 470 430	470 445 400	450 425 390	440 410 370	430 395 355	410 380 365	390 355 305	10,000 10,000 10,000
													175	1000 2000 4000	370 350 335	355 340 315	345 330 300	335 325 290	325 315 280	315 310 270	300 290 260	10,000 10,000 10,000
														212	500 1000 2000	335 325 325	310 300 275	295 280 255	285 270 235	275 265 220	260 245 200	245 245 170
													248	1000 2000	325 295	305 285	290 265	285 250	275 240	265 235	255 210	10,000 10,000
	Nylafil G 3/30	Nylon 6, 30% glass fiber reinforced, inj. molding	Fed. Spec. LP 395 B	IM	RB	11	F2	J	DN (no conditioning) ¹¹	73	8000 100 180 240	830 510 470 380	790 480 450 350	740 475 440 335	720 460 430 320							
	Thermocomp PF-1006	Nylon 6, 30% glass fiber reinforced, inj. molding	Fed. Spec. LP 395 A Type I	IM	RB	11	F4	7	Equilib. with 50% RH ¹⁰	75	5000 10,000		770 680	640 580	625 525	610 510	600 500					
Thermocomp PF-1006 FR	Nylon 6, 30% glass fiber reinforced, VO flame ret. inj. molding		IM	RB	11	F4	7	Equilib. with 50% RH ¹⁰	75	5000		660	570	550	540	520						
Thermocomp PF-1006	Nylon 6, 30% glass fiber reinforced, 15% PTFE lub. inj. molding		IM	RB	11	F4	1	Equilib. with 50% RH ¹⁰	75	2000		910	620	540	500	490						
Nylafil C 13/40	Nylon 6, 40% glass fiber reinforced, inj. molding	Fed. Spec. LP 395 B	IM	RB	11	F2	3	Dry (no conditioning) ¹²	73	10,000	1110	1000	935	865								
										100	10,000	950	870	840	810							
										180	10,000	769	730	700	680							
									240	10,000	665	620	580	555								

^aSee p. 3-107 for explanatory notes

(continued)

TABLE 3-6 (cont'd)

Material	Description	Fed. Spec.	IM	T2	R	T	1	Dry (no conditioning)*	73	4000	1600	1800	1500	1400		1300	200	
									250	2000	450	360	330	300	280	190		
Plaskon 8245	Nylon 6, 40% asbestos reinforced, inj. molding		IM	T2	R	T	1	Dry (no conditioning)*	73	4000	1600	1800	1500	1400		1300	200	
								Equilib. with 50% RH**	73	4000	440	360	330	290	260		250	450
Nylafil G 1/30	Nylon 6/6, 30% glass fiber reinforced, inj. molding	Fed. Spec. LP 395 R	IM	RB	11	F2	3	Dry (no conditioning)†	73	10,000	1250	950	875	830				
								100	10,000	740	670	650	650					
								180	10,000	650	615	600	600					
								240	10,000	506	470	455	445					
Thermocomp RF 1006 FR	Nylon 6/6, 30% glass fiber reinforced, VO flame ret., inj. molding		IM	RB	4	F4	3	Equilib. with 50% RH**	75	5000	-	725	640	600	580	570		
								Equilib. with 50% RH**	75	2000	-	930	650	600	580	560		
Thermocomp RFL 4036	Nylon 6/6, 40% glass fiber reinforced, 15% PTFE lub., inj. molding		IM	RB	4	F4	3	Equilib. with 50% RH**	75	2000	-	930	650	600	580	560		
								Equilib. with 50% RH**	75	2000	-	930	650	600	580	560		
Zytel 79G-332	Nylon 6/6, 33% glass fiber reinforced, inj. molding	Fed. Spec. LP 395 B Type I	IM	RB	4	F4	3	Dry (no conditioning)*	300	4000	535	485	463	440	415	390	340	10,000
								Equilib. with 50% RH**	73	4000	765	700	670	640	615	585	560	460
Maranyl A 190	Nylon 6/6, 43% glass fiber reinforced, inj. molding		IM	TB	10	T	1A		68	3000	1500	1490	1430	1360	1240	1040	596	13,900
									7000	1440	1370	1320	1220	1100	966			
									10,000	1410	1330	1260	1160	1040	885			
								212	7000	526	477	457	434	414	381	346	13,900	
Celanese 1501	Nylon 6/6, 33% glass fiber reinforced, heat stab		IM	RB	4	F4	3	Dry (no conditioning)*	300	4000	535	485	463	442	417	392	341	10,000
								Equilib. with 50% RH**	73	6000	1400	1350	1300	1200	1100			
								Equilib. with 50% RH**	73	4000	770	730	670	630	600	580		
Nylafil R 10/40	Nylon 6/6, 40% glass fiber reinforced, inj. molding	Fed. Spec. LP 395 B	IM	RB	11	F2	3	Dry (no Conditioning)**	73	10,000	1620	1590	1540	1520				
								100	10,000	1350	1280	1250	1220					
								180	10,000	1140	1090	1080	1060					
								240	10,000	1060	1000	975	950					
Thermocomp RF 1008	Nylon 6/6, 40% glass fiber reinforced, inj. molding		IM	RB	4	F4	3	Equilib. with 50% RH**	75	5000		1425	1200	1070	1020	1000		
								Equilib. with 50% RH**	75	10,000		1300	1150	1080	1050	1040		
Zytel 70G-43c	Nylon 6/6, 43% glass fiber reinforced, inj. molding	Fed. Spec. LP 395 B Type II	IM	RB	4	F4	3	Dry (no conditioning)*	259	3000	730	670	640	610	580	550	520	3000
								Equilib. with 50% RH**	73	4000	1010	940	900	860	830	790	755	3000
								Equilib. with 50% RH**	140	4000	900	845	815	780	750	715	685	3000
Thermocomp RF 100-12	Nylon 6/6, 50% glass fiber reinforced, inj. molding		IM	RB	4	F4	3	Equilib. with 50% RH**	75	5000		2000	1710	1550	1470	1430		
								Equilib. with 50% RH**	75	10,000		1780	1650	1580	1570	1560		
Thermocomp RC1006	Nylon 6/6, 30% carbon fiber reinforced, inj. molding		IM	RB	4	F4	3	Equilib. with 50% RH**	73	2500		1780	1560	1430	1350	1315		
								Equilib. with 50% RH**	73	5000		1470	1430	1330	1315	1300		
Thermocomp RC1006	Nylon 6/6, 40% carbon fiber reinforced, inj. molding		IM	RB	4	F4	3	Equilib. with 50% RH**	73	2500		2080	2000	1960	1920	1900		
								Equilib. with 50% RH**	73	5000		1920	1900	1900	1900	1900		

(continued)

TABLE 3-6 (cont'd)

MATERIAL (thermoplastics)				TEST SPECIMEN ¹			CREEP TEST CONDITIONS ²					CREEP TEST DATA ³								
Plastic	Trade Name ¹ and Grade Designation	Grade Description	ASTM, Military, or Other Specification Classification	Method	Type or Shape	Dimensions	Type of Load	Strain Measure	Special Specimen Conditioning	Test temp., °F	Initial ³ Applied Stress, psi	Creep (apparent) Modulus, ⁵ ksi							Time at Latest Test Point, h	Time of Rupture ⁶ or Onset of Yielding at Initial Applied Stress in Air, h
												Calculated from total creep strain or deflection (before rupture and onset of yielding) at the following test times:								
												1 h	10 h	30 h	100 h	300 h	1000 h	at latest test point		
Nylon	Vydene R 100 Creep data also apply to Vydene R 200	Nylon 6/6, mineral filled, inj. mldg. Heat stab		IM	T	16	T	1	Equilib. with 50% RH ¹⁰	73	2000	460	380	330	290	200	150			
	Nylafil G 2/30	Nylon 6/10, 30% glass fiber reinforced, inj. molding	Fed Spec LP-395 B	IM	RB	11	F2	3	Dry (no conditioning) ¹¹	73	8000	790	705	655	635					
										100	8000	460	420	410	410					
										180	8000	430	360	350	340					
										240	8000	380	310	295	270					
	Thermocomp QF-1006 FR	Nylon 6/10, 30% glass fiber reinforced, VO flame ret inj. molding		IM	RB	4	F4	3	Equilib. with 50% RH ¹⁰	75	5000	—	670	580	550	530	510			
	Thermocomp QFL-4036	Nylon 6/10, 30% glass fiber reinforced, 15% PTFE lub inj. molding		IM	RB	4	F4	3	Equilib. with 50% RH ¹⁰	75	2000	—	910	610	550	500	480			
	Nylafil G 12/40	Nylon 6/10, 40% glass fiber reinforced, inj. molding	Fed Spec LP-395 B	IM	RB	11	F2	3	Dry (no conditioning) ¹¹	73	10,000	1210	1070	1010	950					
										100	10,000	900	850	830	815					
										180	10,000	745	720	705	680					
										240	10,000	730	705	675	650					
	Thermocomp QF-1006	Nylon 6/10, 40% glass fiber reinforced, inj. molding		IM	RB	4	F4	3	Equilib. with 50% RH ¹⁰	75	5000	—	910	820	780	760	750			
									10,000	—	750	710	680	680	675					
Thermocomp QF 108-12	Nylon 6/10, 60% glass fiber reinforced, inj. molding		IM	RB	4	F4	3	Equilib. with 50% RH ¹⁰	75	5000	—	2100	1560	1470	1400	1385				
									10,000	—	1530	1410	1350	1330	1320					
Grlamid LV-3H	Nylon 12, 30% glass fiber reinforced, inj. molding		IM	T	1	T	1	Equilib. with 65% RH ¹⁰	68	1000	645	570	535	510	480	455	420	10,000		
										2000	540	500	480	465	450	430	385	10,000		
										4000	610	550	520	500	470	450	410	10,000		
										140	1000	450	415	405	390	380	370	350	10,000	
										2000	345	315	305	285	280	265	250	250	10,000	
										176	500	375	340	325	310	295	280	260	10,000	
										1000	340	305	280	265	255	240	220	220	10,000	
										2000	245	220	205	185	170	160	130	130	10,000	
										212	500	280	265	250	240	235	220	205	10,000	
										1000	275	250	240	230	225	220	210	210	10,000	
										2000	235	220	210	206	203	185	155	155	10,000	

^aSee p. 3-107 for explanatory notes

(continued)

TABLE 3-6 (cont'd)

Phenylene oxide-based resins	NorVISE 1 Creep data also apply to NorVISE 265	G-p (in) molding E-p (extrusion)		IM	RB	4	F4	3		73	1000	393	392	385	376	358	334	265	12,000		
												2000	357	350	347	338	318	294	251	12,000	
												3000	345	325	321	311	289	261	229	12,000	
		NorVISE 100 Creep data also apply to NorVISE 212	Flame ret (in) molding Flame ret (extrusion)		IM	RB	4	F4	3		150	1000	291	275	263	257	243	242	167	13,000	
												2000	290	248	224	211	185	172	135	13,000	
												3000	294	245	200	177	163	145		1000	
		NorVISE 100 Creep data also apply to NorVISE 265	Flame ret (in) molding Flame ret (extrusion)		IM	RB	4	F4	3		170	800	242	196	178	170	160	148	123	13,000	
												1000	237	203	188	171	162	148	123	13,000	
													1500	235	175	161	149	137	130	111	13,000
		NorVISE 100 Creep data also apply to NorVISE 212	Flame ret (in) molding Flame ret (extrusion)		IM	RB	4	F4	3		212	500	217	176	167	143	128	114	54	9400	
											1500	232	190	178	147	134	111	65	9400		
												2000	236	196	184	154	134	115	77	9804	
	NorVISE 100 Creep data also apply to NorVISE 212	Flame ret (in) molding Flame ret (extrusion)		IM	RB	4	F4	3			3000	230	204	183	156	134	115	87	3264	5820 1700	
											1500	428	416	410	395	366	320	269	12,000		
												2000	351	348	344	337	320	294	247	12,000	
	NorVISE 100 Creep data also apply to NorVISE 265	Flame ret (in) molding Flame ret (extrusion)		IM	RB	4	F4	3		150	1000	284	265	253	248	241	235	167	13,000		
												2500	288	248	222	203	185	161	121	13,000	
												3000	297	242	210	188	172	150		1000	
	NorVISE 100 Creep data also apply to NorVISE 212	Flame ret (in) molding Flame ret (extrusion)		IM	RB	4	F4	3		170	1000	233	200	198	170	159	138	123	13,000		
												1500	228	174	158	132	131	120	107	13,000	
												3000	363	340	329	312	284	244			
	Thermocomp 2F-1006	40% glass fiber reinforced (in) molding		IM	RB	4	F4	3		170	2000	625	526	493	470	464	445	396	13,000		
												2500	660	510	481	454	440	438	360	13,000	
												3500	745	580	530	425	374	322			
	Thermocomp LF-1006 FR	40% glass fiber reinforced. VI flame ret (in) molding		IM	RB	4	F4	3		73	2000	1140	1126	1125	1125	1080	1040	954	12,000		
												4000	1070	1065	1060	1053	1025	978	870	12,000	
													4000	970	965	953	950	940	940	815	12,000
	Thermocomp LF-1006 FR	40% glass fiber reinforced. VI flame ret (in) molding		IM	RB	4	F4	3		150	2000	1040	1020	998	977	966	966	866	13,000		
												3000	1067	1030	990	966	945	862	594	13,000	
													170	2000	918	875	830	849	802	686	13,000
	Arylon T-3189	Heat resistant shut extrusion (in) molding		IM	T1	1	T	1		212	3000	950	867	848	786	754	710	543	13,000		
												4000	1010	878	773	725	670	617		13,000	
													5000	833	758	715	638	618	582	427	9400
	Lexan 101-111 Creep data also apply to Lexan 101-111	G-p (in) molding	Fed. Spec .P 393 A	IM	RB	4	F4	3		73	2000	309	300	283	252	218	185				
												3000	277	242	221	197	174	150			
													4000	267	231	211	188	164	138		
	Lexan 101-111 Creep data also apply to Lexan 101-111	G-p (in) molding	Fed. Spec .P 393 A	IM	RB	4	F4	3		180	500	240	191	169	147	127	103				
												1000	279	236	206	168	133	95			
													1500	286	243	200	154	115	81		
	Lexan 101-111 Creep data also apply to Lexan 101-111	G-p (in) molding	Fed. Spec .P 393 A	IM	RB	4	F4	3			2500	263	189	154	114						
												3000	345	333	328	320	315	310			
													1500	300	260	240	225	210	197	190	12,200
	Lexan 101-111 Creep data also apply to Lexan 101-111	G-p (in) molding	Fed. Spec .P 393 A	IM	RB	4	F4	3		160	500	225	200	196	183	180	189	189	11,000		
												1000	245	220	210	200	188	178	165	11,000	
													1500	240	215	205	190	180	170	145	11,000
	Lexan 101-111 Creep data also apply to Lexan 101-111	G-p (in) molding	Fed. Spec .P 393 A	IM	RB	4	F4	3		250	500	135	100	85	70	62	55	50	12,100		
													150	105	85	70	62	55	40	12,100	
													2000	302	276	265	250	240	227	221	12,200

(continued)

TABLE 3-6 (cont'd)

MATERIAL (thermoplastics)				TEST SPECIMEN ^a			CREEP TEST CONDITIONS ^a					CREEP TEST DATA ^a										
Plastic	Trade Name ¹ and Grade Designation	Grade Description	ASTM, Military, or Other Specification Classification	■ ■ ■ Test Meth.	Type or Shape	Dimensions	Type of Load	Strain Measure	Special Specimen Conditioning	Test temp., °F	Initial ³ Applied Stress, psi	Creep (apparent) Modulus, ⁵ ksi							Time at Test Point, h	Time at Rupture ⁶ or Onset of Yielding at Initial Applied Stress in Air, h		
												Calculated from total creep strain or deflection (before rupture and onset of yielding) at the following test times:									Time at Test Point, h	Time at Rupture or Onset of Yielding at Initial Applied Stress in Air, h
												1 h	10 h	30 h	100 h	300 h	1000 h	at latest test point				
Polyethylene	Alkathene K1002, black 904	nu density extrusion	ASTM D 1248 Type I, Class C, Cat. 4	CM	TB	1 1/2	T	5	Annealed 1 h (at 100°C)	68	145 290	25.4 22.5	22.0 19.3	20.7 18.1	19.2 17.0	17.9 15.8	16.1 14.5					
	Paxon AA50-003	high density slow molding	ASTM D 1248 Type III Grade 5	CA	T2	5	T	1		73	1250	55	36	31	26	24	22	21	500			
	Paxon AA60-003	high density slow molding and extrusion	ASTM D 1248 Type III Grade 5	CA	T2	5	T	1		73	1250	60	42	37	32	30		27	600	900		
	Bakelite DMD 7014	high density (i) p. inj. molding	ASTM D 1248 Type III	CM	T1	1	F	1		73	250 500 750 1000		139 83 68 60	131 77 65 56	109 60 47 43	91 54 42 40	74 54 46 34	54 46 34	3400 3400 3400 3400			
										105	250 500 750 1000		46 34 32 25	45 33 31 25	41 30 28 24	38 30 28 21	34 28 25 21	3400 3400 2400 350		150 (rupture)		
	Marlex 9050	High density, (i) p. inj. molding	ASTM D 1248 Type III, Grade 3	CM	DC	5	T	1		75	1000 1250 1500	48 42 30	36 30 16	32 25 11	28 21 7.5	26 18*	24			1600 (rupture) 300 (rupture) 150		
	Amoco 30 670 B4	High density (i) p. molding	ASTM D 1248 Type IV, Grade 3	CM	T1	1	T	2		75	1000	123	62	47	36							
	Marlex 5003	Butene-1 copolymer, stress crack resistant, blow molding	ASTM D 1248 Type III, Grade 5	CM	DC	5	T	1		75	750 1000 1250 1500	46 37 30 25	34 27 22 16.3	29 24 18.8 12.3	26 21 17 8.8	25 20 14	24 17 14.1	22 17 12.5	16,600 16,600 16,600	150		
	Stemylan 9309	High-density (i) p. molding			CM	RB		F		32	357 720 1075	204 183 170	155 135 126	123 112 98	105 93 80	86 74 63	71 65 54	48 32 31	10,000 10,000 3,000			
										73	357 720 1075	124 110 94	96 84 72	72 61 51	58 48 40	50 33 31	42 33 20	28 20 18	10,000 10,000 10,000			
										105	178 357 720	71 69 47	54 50 41	46 41 32	40 35 26		28 23 20	21 18	10,000 10,000			
	Ethofil 90/20	20% glass fiber reinforced (i) p. molding			IM	RB	11	F2	3		73	2000	370	340	325	310						
										100	2000	280	250	240	230							
	Thermocomp FF-1004	20% glass fiber reinforced (i) p. molding			IM	RB	4	F4	3	Rt. lib. with 50%	75	2000		345	330	310	270	260				
Thermocomp FF-1006	30% glass fiber reinforced (i) p. molding			IM	RB	14	F4	3		73	500 1500		695 550	625 500	610 470	595 440	595 420					
Ethofil G 90/40	40% glass fiber reinforced (i) p. molding			IM	RB	11	F2	3		73	2000	840	740	700	690							
									100	2000	690	620	580	570								
									140	2000	580	510	490	480								
									180	2000	500	480	460	420								

^aSee p. 3-107 for explanatory notes

(continued)

TABLE 3-6 (cont'd)

MATERIAL (thermoplastics)				TEST SPECIMEN ^a			CREEP TEST CONDITIONS ^a					CREEP TEST DATA ^a								
Plastic	Trade Name ¹ and Grade Designation	Grade Description	ASTM, Military, or Other Specification Classification	Molding Method	Type or Shape	Dimensions	Type of Load	Measur	Special Specimen Conditioning	Test temp., F	Initial ³ Applied Stress, psi	Creep (apparent) Modulus, ⁵ ksi							Time at Latest Test Point, h	Time at Rupture ⁶ or Onset of Yielding at Initial Applied Stress in Air, h
												Calculated from total creep strain or deflection (before rupture and onset of yielding) at the following test times:								
												1 h	10 h	30 h	100 h	300 h	1000 h	at latest test point		
Hostalen PPN 7790 (GV 240)		Homopolymer 30% glass fiber reinforced coupled in molding		IM	RB	21	F7	3		73	1710	755	680	640	585	525	455	395	2100	
Pro-lax PC-072(30)		Modified PI ² 90% glass fiber spl reinforced		DS	T1	1	T	1	Annealed 2 h (at 275° F)	73 176	4000 9000 8500	820 730	730 650	700 600	660 550	620 500	590 450	470	13,000	1000
Hostalen PPN 7190 TV/40		Homopolymer 36% talc filled in molding and extrusion		IM	RB	21	F7	3		73	1710	345	255	220	190			185	144	
Hostalen PPT 7090 AV/40		Homopolymer, 40% asbestos reinforced, in molding		IM	RB	21	F7	3		73	1710	485	385	310	285			230	144	
Amoco Olefil 2626		40% talc filled, in molding	ASTM D 2146 48100	IM	T1	1	T	2		75	1000	1150	800	680	585	470				
Pro-lax PC-072/40		Modified PP 40% glass fiber (spl) reinforced		DS	T1	1	T	1B	Annealed 2 h (at 275° F)	73 176	5000 8000 10,000 11,000	1100 840 750	905 710 640	808 661 580	740 585 525	550 470	630 502	520	8000	8000 Extrap (1000) 100
Profil G 80/40		40% glass fiber reinforced in molding	MIL P 461098 ASTM D 2853 (9)	IM	RB	11	F2	3		73	2000	970	890	850	840					
Thermocomp MF-1008		40% glass fiber reinforced in molding	MIL P 46109A (MR)	IM	RB	11	F4	7		75	2000 5000	100 2000 180	740 600 510	680 510 475	615 475 430	580 430 310				
Hostalen PPN 7790 (GV 240)		Homopolymer 30% glass fiber reinforced coupled in molding		IM	RB	21	F7	3		73	1710	755	680	640	585	525	455	395	2100	
Pro-lax PC-072(30)		Modified PI ² 90% glass fiber spl reinforced		DS	T1	1	T	1	Annealed 2 h (at 275° F)	73 176	4000 9000 8500	820 730	730 650	700 600	660 550	620 500	590 450	470	13,000	1000
Hostalen PPN 7190 TV/40		Homopolymer 36% talc filled in molding and extrusion		IM	RB	21	F7	3		73	1710	345	255	220	190			185	144	
Hostalen PPT 7090 AV/40		Homopolymer, 40% asbestos reinforced, in molding		IM	RB	21	F7	3		73	1710	485	385	310	285			230	144	
Amoco Olefil 2626		40% talc filled, in molding	ASTM D 2146 48100	IM	T1	1	T	2		75	1000	1150	800	680	585	470				
Pro-lax PC-072/40		Modified PP 40% glass fiber (spl) reinforced		DS	T1	1	T	1B	Annealed 2 h (at 275° F)	73 176	5000 8000 10,000 11,000	1100 840 750	905 710 640	808 661 580	740 585 525	550 470	630 502	520	8000	8000 Extrap (1000) 100
Profil G 80/40		40% glass fiber reinforced in molding	MIL P 461098 ASTM D 2853 (9)	IM	RB	11	F2	3		73	2000	970	890	850	840					
Thermocomp MF-1008		40% glass fiber reinforced in molding	MIL P 46109A (MR)	IM	RB	11	F4	7		75	2000 5000	100 2000 180	740 600 510	680 510 475	615 475 430	580 430 310				
Hostalen PPN 7790 (GV 240)		Homopolymer 30% glass fiber reinforced coupled in molding		IM	RB	21	F7	3		73	1710	755	680	640	585	525	455	395	2100	
Pro-lax PC-072(30)		Modified PI ² 90% glass fiber spl reinforced		DS	T1	1	T	1	Annealed 2 h (at 275° F)	73 176	4000 9000 8500	820 730	730 650	700 600	660 550	620 500	590 450	470	13,000	1000
Hostalen PPN 7190 TV/40		Homopolymer 36% talc filled in molding and extrusion		IM	RB	21	F7	3		73	1710	345	255	220	190			185	144	
Hostalen PPT 7090 AV/40		Homopolymer, 40% asbestos reinforced, in molding		IM	RB	21	F7	3		73	1710	485	385	310	285			230	144	
Amoco Olefil 2626		40% talc filled, in molding	ASTM D 2146 48100	IM	T1	1	T	2		75	1000	1150	800	680	585	470				
Pro-lax PC-072/40		Modified PP 40% glass fiber (spl) reinforced		DS	T1	1	T	1B	Annealed 2 h (at 275° F)	73 176	5000 8000 10,000 11,000	1100 840 750	905 710 640	808 661 580	740 585 525	550 470	630 502	520	8000	8000 Extrap (1000) 100
Profil G 80/40		40% glass fiber reinforced in molding	MIL P 461098 ASTM D 2853 (9)	IM	RB	11	F2	3		73	2000	970	890	850	840					
Thermocomp MF-1008		40% glass fiber reinforced in molding	MIL P 46109A (MR)	IM	RB	11	F4	7		75	2000 5000	100 2000 180	740 600 510	680 510 475	615 475 430	580 430 310				
Hostalen PPN 7790 (GV 240)		Homopolymer 30% glass fiber reinforced coupled in molding		IM	RB	21	F7	3		73	1710	755	680	640	585	525	455	395	2100	
Pro-lax PC-072(30)		Modified PI ² 90% glass fiber spl reinforced		DS	T1	1	T	1	Annealed 2 h (at 275° F)	73 176	4000 9000 8500	820 730	730 650	700 600	660 550	620 500	590 450	470	13,000	1000
Hostalen PPN 7190 TV/40		Homopolymer 36% talc filled in molding and extrusion		IM	RB	21	F7	3		73	1710	345	255	220	190			185	144	
Hostalen PPT 7090 AV/40		Homopolymer, 40% asbestos reinforced, in molding		IM	RB	21	F7	3		73	1710	485	385	310	285			230	144	
Amoco Olefil 2626		40% talc filled, in molding	ASTM D 2146 48100	IM	T1	1	T	2		75	1000	1150	800	680	585	470				
Pro-lax PC-072/40		Modified PP 40% glass fiber (spl) reinforced		DS	T1	1	T	1B	Annealed 2 h (at 275° F)	73 176	5000 8000 10,000 11,000	1100 840 750	905 710 640	808 661 580	740 585 525	550 470	630 502	520	8000	8000 Extrap (1000) 100
Profil G 80/40		40% glass fiber reinforced in molding	MIL P 461098 ASTM D 2853 (9)	IM	RB	11	F2	3		73	2000	970	890	850	840					
Thermocomp MF-1008		40% glass fiber reinforced in molding	MIL P 46109A (MR)	IM	RB	11	F4	7		75	2000 5000	100 2000 180	740 600 510	680 510 475	615 475 430	580 430 310				
Hostalen PPN 7790 (GV 240)		Homopolymer 30% glass fiber reinforced coupled in molding		IM	RB	21	F7	3		73	1710	755	680	640	585	525	455	395	2100	
Pro-lax PC-072(30)		Modified PI ² 90% glass fiber spl reinforced		DS	T1	1	T	1	Annealed 2 h (at 275° F)	73 176	4000 9000 8500	820 730	730 650	700 600	660 550	620 500	590 450	470	13,000	1000
Hostalen PPN 7190 TV/40		Homopolymer 36% talc filled in molding and extrusion		IM	RB	21	F7	3		73	1710	345	255	220	190			185	144	
Hostalen PPT 7090 AV/40		Homopolymer, 40% asbestos reinforced, in molding		IM	RB	21	F7	3		73	1710	485	385	310	285			230	144	
Amoco Olefil 2626		40% talc filled, in molding	ASTM D 2146 48100	IM	T1	1	T	2		75	1000	1150	800	680	585	470				
Pro-lax PC-072/40		Modified PP 40% glass fiber (spl) reinforced		DS	T1	1	T	1B	Annealed 2 h (at 275° F)	73 176	5000 8000 10,000 11,000	1100 840 750	905 710 640	808 661 580	740 585 525	550 470	630 502	520	8000	8000 Extrap (1000) 100
Profil G 80/40		40% glass fiber reinforced in molding	MIL P 461098 ASTM D 2853 (9)	IM	RB	11	F2	3		73	2000	970	890	850	840					
Thermocomp MF-1008		40% glass fiber reinforced in molding	MIL P 46109A (MR)	IM	RB	11	F4	7		75	2000 5000	100 2000 180	740 600 510	680 510 475	615 475 430	580 430 310				
Hostalen PPN 7790 (GV 240)		Homopolymer 30% glass fiber reinforced coupled in molding		IM	RB	21	F7	3		73	1710	755	680	640	585	525	455	395	2100	
Pro-lax PC-072(30)		Modified PI ² 90% glass fiber spl reinforced		DS	T1	1	T	1	Annealed 2 h (at 275° F)	73 176	4000 9000 8500	820 730	730 650	700 600	660 550	620 500	590 450	470	13,000	1000
Hostalen PPN 7190 TV/40		Homopolymer 36% talc filled in molding and extrusion		IM	RB	21	F7	3		73	1710	345	255	220	190			185	144	
Hostalen PPT 7090 AV/40		Homopolymer, 40% asbestos reinforced, in molding		IM	RB	21	F7	3		73	1710	485	385	310	285			230	144	
Amoco Olefil 2626		40% talc filled, in molding	ASTM D 2146 48100	IM	T1	1	T	2		75	1000	1150	800	680	585	470				
Pro-lax PC-072/40		Modified PP 40% glass fiber (spl) reinforced		DS	T1	1	T	1B	Annealed 2 h (at 275° F)	73 176	5000 8000 10,000 11,000	1100 840 750	905 710 640	808 661 580	740 585 525	550 470	630 502	520	8000	8000 Extrap (1000) 100
Profil G 80/40		40% glass fiber reinforced in molding	MIL P 461098 ASTM D 2853 (9)	IM	RB	11	F2	3		73	2000	970	890	850	840					
Thermocomp MF-1008		40% glass fiber reinforced in molding	MIL P 46109A (MR)	IM	RB	11	F4	7		75	2000 5000	100 2000 180	740 600 510	680 510 475	615 475 430	580 430 310				
Hostalen PPN 7790 (GV 240)		Homopolymer 30% glass fiber reinforced coupled in molding		IM	RB	21	F7	3		73	1710	755	680	640	585	525	455	395	2100	
Pro-lax PC-072(30)		Modified PI ² 90% glass fiber spl reinforced		DS	T1	1	T	1	Annealed 2 h (at 275° F)	73 176	4000 9000 8500	820 730	730 650	700 600	660 550	620 500	590 450	470	13,000	1000
Hostalen PPN 7190 TV/40		Homopolymer 36% talc filled in molding and extrusion		IM	RB	21	F7	3		73	1710	345	255	220	190			185	144	
Hostalen PPT 7090 AV/40		Homopolymer, 40% asbestos reinforced, in molding		IM	RB	21	F7	3		73	1710	485	385	310	285			230	144	
Amoco Olefil 2626		40% talc filled, in molding	ASTM D 2146 48100	IM	T1	1	T	2		75	1000	1150	800	680	585	470				
Pro-lax PC-072/40		Modified PP 40% glass fiber (spl) reinforced		DS	T1	1	T	1B	Annealed 2 h (at 275° F)	73 176	5000 8000 10,000 11,000	1100 840 750	905 710 640	808 661 580	740 585 525	550 470	630 502	520	8000	8000 Extrap (1000) 100
Profil G 80/40		40% glass																		

TABLE 3-6 (cont'd)

Forma Tuf Flex 721	Impact modif polystyrene, 8-2 Izod molding and extrusion	ASTM D 1892 Type III-6	IM	T1	1	T	1		73	2000	440	220	200							
Forma Tuf Flex 272	Impact modif polystyrene 1-2 1-3 Izod, extrusion	ASTM D 1892 Type III-6	IM	T1	1	T	1		73	2000	335	200	200							
			ES	T1	1	T	1		73	2000	150	140	130							
Lustrez HT92	Impact modif, sheet extrusion		ES	T1	1	T	1		73	2000	351	328	286	253	222	168				
Styron 492	Impact modif. polystyrene. high heat resistant		CM	T3	1	T	1		73	2030 2270 2520	300 265 240	275 215	265 195	245	210		140 190 190	844 46 37	900 (rupture) ¹⁴ 90 (rupture) 4.5 (rupture)	
									100	1050 1470 2020	255 255 230	250 250	240 240	205 205	170 170	130 130	115 100 175	2980 2370 7.5	— — 7.5 (rupture)	
Styrolin G-30/20	20% glass fiber reinforced polystyrene, inj. molding		IM	RB	11	F2	3		73	2000	980	950	940	935						
									100	2000	940	860	770	675						
									140	2000	790	520	460	410						
Thermocomp CF-1004	20% glass fiber reinforced polystyrene, inj. molding		IM	RB	4	F4	3		75	5000 10,000	—	960 900	920 890	890 870	850 790					
Styrolin G-35/15	35% glass fiber reinforced polystyrene, inj. molding	MIL P 21347B	IM	RB	11	F2	3		73	8000	1350	1290	1260	1250						
									100	8000	1240	1150	1050	980						
									140	8000	850	485	450	430						
Thermocomp CF-1007	35% glass fiber reinforced polystyrene, inj. molding		IM	RB	4	F4	3		75	5000 10,000	—	1800 1750	1750 1630	1710 1530	1690 1480	1660 1450				
Astrei 360	Aryl sulphone, g. p. inj. molding and extrusion	MIL P-46133(MR)	IM	T1	1	T	1		73	8200 10,000	2730 —	1950 1280	1640 780	1365 585						
									293	4450	254	110	74							
ICI 300 P	Ether sulphone, inj. molding		IM	T	16	T	1A		72	300	4000 1000	350 365	335 320	330 300	320 250	315 230	310 230	275 140	28,000 28,000	
ICI 200 P	Ether sulphone, 40% glass fiber-reinforced		IM	T1	1	T	1A	2 h at 356° F (prior to test) 2 weeks at 356° F	356	4350	1280	906	737	670	564	530				
									356	4350	1673	1553	1450	1400	1240	1175				
Udel P 1700 Comp data also apply to: Udel P 3500 Udel P 1720	Inj. molding (6.5MFR) Extrusion (3.5 MFR) V0 flame ret. (6.5MFR)	MIL P 46120	IM	T	16	T	2		72	4000	—	345	—	340	—	325	280	20,000		
									212	3000	—	240	—	215	—	190	170	20,000		
									300	1000	—	140	—	100	—	75	50	10,000		
			IM	RB	4	F4	3		140	3500	—	330	—	320	—	310	275	20,000		
									257	2000	—	210	—	170	—	140	120	10,000		
Thermocomp GF-1006	30% glass fiber reinforced, inj. molding		IM	RB	14	F4	3		210	2000 3000	—	1000 800	870 670	770 620	740 610	740 600				
Thermocomp GF-1006 FR	30% glass fiber reinforced, V0 flame ret., low smoke, inj. molding		IM	RB	4	F4	3		75	5000	—	1000	860	800	780	770				
Thermocomp GPL-4036	30% glass fiber reinforced, 15% PTFE lub., inj. molding		IM	RB	4	F4	3		75	2000	—	1200	1050	910	870	860				
Thermocomp GC-1006	30% carbon fiber reinforced, inj. molding		IM	RB	4	F4	3		73	2500 5000	—	1810 1710	1700 1660	1570 1570	1490 1550	1410 1450				
Thermocomp GF-1008	40% glass fiber reinforced, inj. molding		IM	RB	4	F4	3		75	5000 10,000	—	1560 1580	1500 1520	1450 1500	1450 1490					
Halon G 80	High mechanical performance, g. p. molding resin	ASTM D 1457 Type IV, Class 3	CE	D1	8	T	1		73	500 650 850 1000 1250	50 38 22 17 15 12 9.6	39 30 15 13 10 8 5.9	34 26 13 11 8 3.7	29 23 11 6 3.0	26 20 18 8 5 2.6	23 18 14 10 3 2.6	18 14 8 3 2.6	8616 8616 8616 8616 575		
									100	500	30	22	19	16	14	11	9	5300		
									120	500	20	16	14	13	12	10	9	4950		

(continued)

TABLE 3-6 (cont'd)

Polytetrafluoroethylene (PTFE) (Cont'd)	Teflon 7 Creep data also apply to Teflon 7A, 7B, 7C	High mechanical performance, z p molding resin	ASTM D 1457 Type IV	CG	RS	5 6	T	2		65	1000 2000 3000	17R 9.5 60	178 89 41	178 82 38	178 73 25			178 70 24	115 115 115
										73	500 1000	60 17.5	44 10.5	38 8.1	32 6.3			30 5.6	160 160
										212	200 500 580	16.6 6.2 4	14.8 5 3.1	13.8 4.4 2.8	12.9 4.3 2.4			12.9 4.2 2.2	200 120 180
										392	100 200 300	7.1 5.9 2.5	5.7 4.6 2.1	5.3 4.2 1.9	5 3.6 1.8			4.9 3.5 1.7	140 140 140
				CH	CR	7	C	4		73	500 1000 1750	50 40 21	42 33 17.5	40 30 15.9	37 28	35		34 27 15.2	330 140 70
										212	200 500 750	2.5 12.9 11.5	19 16.1 9.3	14.8	10.2			14.3 10 8.8	125 160 50
	Fluon G 161	High mechanical performance, z p molding resin	ASTY D 1457 Type IV, Class 3	CI	HC	18	C	5		68	125	59.5	49	44	40	36	33		
	Fluorofil G20	20% glass fiber reinforced		CG	RC	7	C	4		73	2000 500	65 17	47 14	45 13	42 12	40		11	150
	Fluorofil G25	25% carbon fiber-reinforced		CG	RC	7	C	4		73	2000	50	42	40	38	36			
	Fluon VG 25	25% glass fiber-reinforced, molding compound		CI	HC	18	C	5		68	200 400 600 800 1000 1200 1400	200 174 154 133 118 102 91	154 133 122 109 94 85 77 68	133 121 108 100 92 85 78 60	118 108 100 92 85 78 73 66 61 55 51 42	108 100 91 73.5 68 66 61 55 51 42	73 73.5 68 66 55	10,000 6000 6000 3000 3000	
Polystyrene-acrylonitrile (SAN)	Tyrl 867	G p		CM	T3	1	T	1		73	4400 4920 5500 6030 8460 6870	500 475 490 475 470 460	475 455 410 435 430	425 425 355 330	385 385 285	325 315	250 290 285 309 275 370 440	3500 1705 284 190 47 6	4390 (rupture) 1410 (rupture) 284 (rupture) 152 (rupture) 55 (rupture) 4.7 (rupture)
	Acrylafil G 40/20	20% glass fiber reinforced, inj molding		IM	RR	11	F2	3		73	2000 100 140	1130 890 2000	1090 720 360	1070 600 330	970 530 310				
	Thermocomp BF 1004	20% glass fiber reinforced inj molding		IM	RB	4	F4	3		75	5000		1100	1040	1000	960	920		
	Thermocomp RF 1006 FR	30% glass fiber reinforced, V 0 flame ret inj molding		IM	RB	4	F4	3		75	5000		1400	1300	1250	1250	1250		
	Acrylafil G 40/35	35% glass fiber reinforced inj molding		IM	RB	11	F2	3		73	2000 100 140	1680 1140 2000	1620 890 820	1570 790 630	1500 720 620				
	Thermocomp BF 1006	40% glass fiber reinforced inj molding		IM	RB	4	F4	3		75	10,000		1800	1700	1630	1590	1550		
Polyurethane	LNPTF-1008	40% glass fiber reinforced, inj molding		IM	RB	4	F4	3		75	500		160	135	130	125	125		
Mylar	Bakelite QNDA 2201	High impact, rigid molding compound	ASTM D 1784 Type II, CR. 1 and Type III, CR. 1	CM	T1	1	T	1		73	1000 1500 2000	330 300 294			250 241	220 222		125 120 116	20,000 20,000 20,000
	Darvic Natural 110	Rigid, annealed		CL	TB	10	T	1A	Stored 17 mo at 68° F., 65% RH	68	1450 3625 4350	439 417 368	426 386 338	414 362 311	339			400 339 298	72 400 47
	Thermocomp VF-1003	25% glass fiber-reinforced, molding compound		IM	RB	4	F4	3		75	5000 10,000		1360 1330	1300 1220	1260 1220	1230 1180	1210 1140		

(continued)

TABLE 3-6 (cont'd)

MATERIAL (thermoplastics)			TEST SPECIMEN ^a	CREEP TEST CONDITIONS ^a				CREEP TEST DATA ^a											
Plastic	Trade Name ¹ and Grade Designation	Grade Description	ASTM, Military, or Other Specification Classification	Molding Method	Type or Shape	Dimensions	Type of Load	Strain Measure	Special Specimen Conditioning	Test temp., °F	Initial ³ Applied Stress, psi	Creep (apparent) Modulus, ⁵ ksi						Time at Test Point, h	Time at Rupture ⁶ or Onset of Yielding at Initial Applied Stress in Air, h
												Calculated from total creep strain or deflection (before rupture and onset of yielding) at the following test times:							
												1 h	10 h	30 h	100 h	300 h	1000 h		
Vinyl (Cont'd)	Sta-flow 2003 A Creep data also apply to: 2019 2020 2025 2029 5011 7021 7029	Propylene vinyl chloride copolymer molding and extrusion compound med imp opaque Clear hatters Clear med imp Clear high imp Clear high imp Clear extra high imp Opaque high imp Clear med imp		CM	T	20	T	1	48 h at 23 °C 50% RH	73	3850	350	451	320	240	175	128		
											4000	330	345	272	174	132			
											4300	305	252	183	142				
											4600	317	209	152					
											4900	350	162						
											5500	192							

^aSee p. 3-107 for explanatory notes

EXPLANATORY NOTES FOR TABLE 3-6

¹Registered trade name.

²In tensile bars, dimensions are of the reduced section.

Calculation of initial applied stress:

a. In tension:

$$\text{applied stress} = \frac{\text{applied load (lb)}}{\text{initial area (in}^2\text{) of reduced or strip cross section perpendicular to applied load}}, \text{ psi}$$

b. In compression:

$$\text{applied stress} = \frac{\text{applied load (lb)}}{\text{initial area (in}^2\text{) of cross section perpendicular to applied load}}, \text{ psi}$$

c. In simple beam bending of a rectangular beam:

$$\text{applied stress} = \text{max fiber stress} = \frac{3PL}{2bd^2}, \text{ psi}$$

where

- P = initial applied load, lb
- L = span, in.
- b = width of beam, in.
- d = depth of beam, dimension parallel to direction of applied load, in.

NOTE: This equation is an approximation for most plastics at most test conditions. Its use leads to significant variations in calculated stress with bar dimensions, span, and all but small strains. See ASTM D790.

Calculation of strain at any time T:

a. In tension:

$$\epsilon_t = \frac{\Delta L}{L}, \text{ in./in.}$$

where

- ϵ_t = strain in tension, in./in.
- ΔL = total change in gage length at time T, in.
- L = initial gage length, in.

b. In compression:

$$\epsilon_c = \frac{\Delta H}{H}, \text{ in./in.}$$

where

- ϵ_c = strain in compression, in./in.
- ΔH = total change in height at time T, in.
- H = initial height, in.

c. In simple bending of a rectangular beam:

deflection at time T = total movement (in.) of center of beam at the time T of point of application of load.

NOTE: For strain calculations see ASTM D790.

Calculation of creep (apparent) modulus at any time T:

a. In tension or compression:

$$\text{creep modulus} = \frac{\text{initial applied stress (psi)}}{\text{total strain (in./in.)}}, \text{ psi}$$

b. In simple beam bending

$$\text{creep modulus} = \frac{PI^2}{48I\Delta}, \text{ psi}$$

where

- P = initial applied load, lb
- L = span, in.
- A = measured deflection of the center of beam at time T at point of application of load, in.
- I = moment of inertia of beam, in⁴

For a rectangular beam:

$$I = \frac{bd^3}{12}, \text{ in}^4$$

where

- b = beam width, in.
- d = beam depth, dimension parallel to direction of applied load, in.

⁴Where no value for time at rupture or onset of yielding is shown, rupture or yielding did not occur during the particular creep test at the particular stress and temperature listed in the chart. The possibility exists, however, that rupture or yielding would have occurred if the test had been continued to longer times, or if tests were made at higher stresses and/or temperatures. See O'Toole, J.L. 'Creep Properties of Plastics' *Modern Plastics Encyclopedia 1968-69 edition*, McGraw-Hill, Inc., New York, N.Y. 10020.

⁵In a set of similar creep tests on the same material where the level of applied stress is varied at constant temperature, the effect of increasing stress normally is to decrease the creep modulus at corresponding test times. This is consistent with experience and with the theory of linear viscoelasticity. However, experimental data occasionally will show the opposite effect, or the creep curves at different stress levels will cross. This is probably due to experimental variation, and in such cases the experimental data may be regarded collectively as estimates of creep behavior over the range of the applied stresses involved.

⁶This situation is most likely to occur at the following test conditions: at small strains (around 1% and less); where levels of applied stress are close; where the number of replicate tests are small. Common sources of experimental variation are: test method reproducibility; specimen-to-specimen variation due to fabrication and composition variables, reproducibility of temperature control; and variation in loading rate and technique. For certain types of stresses, such as bending and compression, it is possible that variation in stress distribution within the specimens at different levels of applied stress also contribute.

⁷In the moisture condition to which this note refers, the nylon is essentially dry, which is the condition of freshly molded parts that have been properly fabricated. However, at this condition (and as pellets properly shipped in sealed vacuum cans) nylon normally contains a small residual amount of moisture, less than 0.3%.

⁸Freshly molded nylon slowly absorbs moisture—which significantly affects its properties—from humid atmospheres, reaching an equilibrium moisture content that depends on the relative humidity and that varies with the type of nylon. The equilibrium moisture content with any particular relative humidity is the highest for nylons 6 and 6/6, significantly lower for nylons 6/10 and 6/12, and least for nylons 12 and 11. The rate of absorption depends on temperature and on the wall thickness of the part; and, for all but very thin sections, months and sometimes years are required to attain equilibrium. For this reason, parts are often artificially conditioned before use to a moisture content equal to that of their projected equilibrium conditions by immersion in hot water for short times. Equilibrium with 50% relative humidity has been found by experience to represent a practical moisture condition for design for many typical nylon parts.

⁹(See also Note 10). The moisture content in the table to which this note refers is the maximum that nylon will absorb, which is equilibrium with liquid water and, therefore, the most severe condition from the standpoint of effect of moisture content on properties. This equilibrium moisture content varies with the type of nylon—being highest for 6 and 6/6, intermediate for 6/10 and 6/12, and least for 12 and 11. It should be noted that the combined effects of moisture content and temperature on mechanical properties are not additive; the effect of moisture absorption being greatest around room temperature but relatively small above 150° F and below 32° F for most nylons.

¹⁰(See Notes 9 and 10) The tests to which this note refers were begun with specimens in the dry condition, but were carried out in a humid atmosphere. Therefore, the specimens were likely to have absorbed small amounts of moisture during the tests.

¹⁵These are average times to failure of replicate tests and, therefore, in some cases are slightly smaller than the longest test times at which creep modulus was measured. Creep was monitored continuously by means of a recording extensometer.

¹⁶Rectangular column, 0.190 in. × 0.190 in. in cross section and 2 in. high, was loaded in column compression after insertion in a closely fitting (to the corners of the column) cylindrical steel tube which prevented buckling. See "A Method for Measuring Compressive Creep of Thermoplastic Materials", by E. D. Jones, G. P. Koo, and J. L. O'Toole, *Materials Research and Standards*, 6,(5 May 1966).

¹⁷Maximum stress recommended by the supplier for 5-yr life

"Explanation of test specimen and creep test conditions' codes:

a. Molding methods:

- CA = Compression molded per ASTM D1928
- CB = Comp. molded; annealed 2 h at 140° C; quenched at 0° C
- CC = Comp. molded; annealed 2 h at 140° C; slow cooled
- CD = Comp. molded; annealed 2 h at 140° C; cooled at 40° C/h
- CE = Comp. molded and free sintered at 700° F; cooled at 170° F/h
- CF = Comp. molded and free sintered at 675° F; cooled at 175° F/h
- CG = Comp. molded and free sintered at 720° F; cooled at 180° F/h
- CH = Comp. molded and free sintered at 720° F; cooled at 300° F/h
- CI = Comp. molded and free sintered at 716° F; cooled at 54° F/h
- CL = Calendered sheet
- CM = Compression molded
- CS = Cast sheet
- DS = Direct blend, screw inj. molded
- ES = Extruded sheet
- IM = Injection molded
- IZ = Inj. molded; mold temp. 265° F
- M = Machined
- TM = Transfer molded

b. Type or shape:

- CR = Cylindrical rod
- DC = Die C per ASTM D412
- D1 = Modified Die C with 3.4 in. reduced section
- HC = Hollow cylinder—see Note 22
- I2 = Tensile bar per ISO R527
- RB = Rectangular bar
- RC = Rectangular column
- RS = Rectangular strip
- T = Tensile bar
- TB = Tensile bar—see Note 19
- T1 = Type 1 tensile bar per ASTM D638
- T2 = Type 2 tensile bar per ASTM D638
- T3 = Type 3 tensile bar per ASTM D638

c. Dimensions, in. (overall for bars and columns, and reduced section for dog bones):

- 1 = 1/2 × 1/8
- 2 = 5 × 1 × 0.090

- 3 = 4 × 1 × 0.026
- 4 = 5 × 1/2 × 1/8
- 5 = 1/4 × 1/16
- 6 = 112 × 1/16
- 7 = 112 diam. × 1 high
- 8 = 114 × 1/8
- 9 = 114 × 1/12
- 10 = 4 × 1/8 × 0.218
- 11 = 5 × 1/2 × 1/16
- 12 = 0.24 × 0.075
- 13 = 5 × 1/32 × 0.392
- 14 = 5 × 112 × 112
- 15 = 16 × 1 × 1/8 or 114
- 16 = 8 × 1/2 × 1/8
- 17 = 0.190 × 0.190 × 2 high
- 18 = 518 ID × F3/4 OD × 2.5 high
- 19 = 0.024 × 0.035
- 20 = 3112 × 1/4 × 1/8
- 21 = 120 × 20 × 6 mm.
(4.72 × 0.79 × 0.25 in.)
- 22 = 0.39 × 0.16

d. Type of load:

- C = Compression
- C1 = Compression—see Note 16
- F = Flexure—simple beam bending, load at center
- F2 = Flexure—simple beam bending, load at center, 2 in. span
- F3 = Flexure—simple beam bending, load at center, 3 in. span
- F4 = Flexure—simple beam bending, load at center, 4 in. span
- F6 = Flexure—uniform beam bending moment, 6 in. span
- F7 = Flexure—4-point loading, constant outside fiber stress—see Note 23
- T = Tension

e. Strain measurement:

- 1 = Strain in reduced section
- 1A = Strain in reduced section—see Note 20
- 1B = Strain in reduced section—see Note 21
- 1C = Strain in reduced section—corrected for shrinkage
- 2 = Grip separation
- 3 = Deflection at center of beam
- 4 = Reduction in height
- 5 = Extensometer—see Note 22.

¹⁹Mills, W. H. and Turner, S., "Tensile Creep Testing of Plastics", *Proc. I. Mech. E.*, **180**, Part 3a, paper 23, p. 291 (1965-66).

²⁰Modified Lamb Extensometer, see Dunn, C. M. R., Mills, W. H., and Turner, S., "Review of Apparatus for Creep Measurements", *British Plastics*, July 1964.

²¹Optical lever extensometer, *ibid.*

²²Thomas, D. A., "Uniaxial Creep of PTFE", 27th SPE ANTEC, Chicago, 1969. Recke, H., *Materialprüfung* Bd., **5**(1963), S.345/349.

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TABLE 3-7. WEAR FACTOR, COEFFICIENT OF FRICTION, LPV, AND TOOTH DECAY STRENGTH OF INTERNALLY LUBRICATED THERMOPLASTICS

Resin	Glass Content, wt %	TFE Content, wt %	Wear Factor K^a (Equilibrium), $\left(\frac{\text{in.}^3 \cdot \text{min}}{\text{ft} \cdot \text{lb} \cdot \text{h}}\right) \times 10^{10}$	Coefficient of Friction		Limited by Journal Half Bearing			Tooth Strength, psi
				Static (40 psi)	Dynamic (40 psi, 50 fpm)	10 fpm	100 fpm	1000 fpm	
			LNP #3	LNP #3		LNP #2			LNP #35
Styrene Acrylonitrile	30	15	65	0.13	0.18	17,500	10,000	10,000	21,500
Polycarbonate	0	0	2,500	0.31	0.38	750	500	NR	—
Polycarbonate	30	15	30	0.18	0.20	30,000	13,000	5,000	25,500
Poly sulfone	30	15	70	0.09	0.11	20,000	35,000	15,000	25,600
Acetal	0	0	65	0.14	0.21	4,000	3,500	<2,500 ^b	—
Acetal	0	20	17	0.07	0.15	40,000	12,500	5,500	—
Acetal	30	15	200	0.20	0.28	12,500	12,000	8,000	9,500
Polypropylene	30	15	36	0.09	0.09	14,000	12,000	7,500 ¹³	15,500
Nylon Type 6	30	15	17	0.20	0.25	17,500	20,000	13,000	30,000
Nylon Type 6/10	30	15	15	0.23	0.31	20,000	15,000	12,000 ^c	28,500
Nylon Type 6/6	0	0	200	D.24	0.26	3,000	2,500	>2,500	—
Nylon Type 6/6	0	20	12	0.10	0.18	40,000	27,500	8,000	—
Nylon Type 6/6	30	15	16	0.19	0.26	17,500	20,000	13,000	31,000
Polyurethane	30	15	35	0.20	0.25	17,500	10,000	5,500	11,800
Polyester	30	15	20	0.16	0.21	40,000	30,000	5,500	12,600

^aWear factor values are to be multiplied by 10^{10} . Values given are for 50 fpm, 40 psi, 2,000 PV. A material with a wear factor $K = 1$ will wear 1 in.^3 supporting a load of 1 lb at a speed of 1 fpm in 1 h. Radial bearing wear is determined from $R = KPV T$, where $P = F/A$, lb/in.² projected area; $V =$ velocity, fpm; and $T =$ time, h.

^bLow load limit at 1,000 fpm.

^cMated against SAE 1040 steel.

TABLE 3-8. WEAR AND FRICTIONAL PROPERTIES OF THERMOPLASTIC RESINS AND COMPOSITES¹⁴

Base Resin	TFE, % wt	Glass Content, % wt	K-factor ^b , $\left(\frac{\text{in.}^3 \cdot \text{min}}{\text{ft} \cdot \text{lb} \cdot \text{h}}\right) \times 10^{-10a}$	Coefficient of Friction	
				Static (40 psi)	Dynamic (40 psi, 50 fpm)
Styrene Acrylonitrile	—	—	3,000	0.28	0.33
Styrene Acrylonitrile	15	—	200	0.11	0.14
Styrene Acrylonitrile	15	30	65	0.13	0.18
Polycarbonate	—	—	2,500	0.31	0.38
Polycarbonate	15	—	75	0.09	0.15
Polycarbonate	15	30	30	0.18	0.20
Polycarbonate	15	40	45	0.20	0.23
Polysulfone	15	—	46	0.10	0.09
Polysulfone	15	30	55	0.12	0.10
Polysulfone	—	40	82	0.24	0.20
Acetal	—	—	65	0.14	0.21
Acetal	5	—	40	0.12	0.18
Acetal	10	—	30	0.10	0.17
Acetal	15	—	20	0.07	0.15
Acetal	20	—	17	0.07	0.15
Acetal	15	30	200	0.20	0.28
Acetal (mated against acetal K1000)	—	—	10,200	0.19	0.15
Acetal (mated against nylon 6/6 RL4040)	20	—	30	0.03	0.04
Polypropylene	20	—	41	0.05	0.11
Polypropylene	15	30	36	0.09	0.09
Nylon 6	—	—	200	0.22	0.26
Nylon 6	15	—	15	0.09	0.19
Nylon 6	15	30	17	0.20	0.25
Nylon 6/10	15	30	15	0.23	0.31
Nylon 6/6	—	—	200	0.20	0.28
Nylon 6/6	5	—	60	0.13	0.20
Nylon 6/6	20	—	12	0.10	0.18
Nylon 6/6	15	30	16	0.19	0.26
Nylon 6/6	—	10	80	0.17	0.16
Nylon 6/6	—	30	75	0.21	0.20
Nylon 6/6	—	40	70	0.22	0.21
Nylon 6/6	—	60	44	0.23	0.21
Nylon 6/6 (mated against nylon 6/6 R 1000)	—	—	1,150	0.12	0.11
Nylon 6/6 (mated against nylon 6/6 RL4040)	—	—	30	0.08	0.05
Nylon 6/6 (mated against nylon 6/6 K1000)	—	—	49	0.04	0.05
Nylon 6/6 (mated against acetal Fulton 404)	20	—	12	0.03	0.04
Polyurethane	—	—	340	0.32	0.37
Polyurethane	15	30	35	0.20	0.25
Polyester (PST)	15	30	20	0.16	0.21
Chlorotrifluoroethylene	—	—	110	0.54	0.51
Chlorotrifluoroethylene	15	—	14	0.14	0.17
Ethylene tetrafluoroethylene (Tefzel)	—	25	16	0.24	0.28
Ethylene tetrafluoroethylene	15	25	11	0.16	0.14
Polyphenylene Sulfide (Ryton)	—	—	540	0.30	0.24
Polyphenylene Sulfide	15	0	110	0.17	0.15

^aK-factor values to be multiplied by 10⁻¹⁰.^bMated against SAE 1040 steel unless otherwise noted.

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TABLE 3-9. COMPARISON OF THE THERMAL PROPERTIES OF GLASS-REINFORCED THERMOPLASTICS

Polymer System	Glass Content, wt %	Property ASTM Method	Deflection 66 psi 0648	Temp., °F 264 psi 0648	Coef. of Thermal Expansion, $(\frac{\text{in.}}{\text{in.} \cdot \text{°F}}) \times 10^{-5}$ 0696	Coef. of Thermal Conductivity, Btu he ft ² °F/in. CenCo	Maximum UL Temp Index/UL Temp Index Resistance to Impact Not Essential, °C ^b UL	Flammability			Deformation Under Load 2000 psi, 24 h, 50° C, % D621
								0.125 in. Specimen ASTM, in. in./min 0635	UL Subj 94	1/8 in. x 1/4 in. Specimen Oxygen Index, % O ₂ D2863	
Acetal	0		316	230	4.1	1.7	80190	—	94HB	—	1.0
	20		345	315	—	2.0	851105	0.8	—	—	—
	30		325	320	2.4	22	961—	—	94HB	16	0.60
	40		325	320	1.8	23	—	SB	94HB	—	—
Acrylic	0		225	210	—	—	—	—	—	—	—
	20		—	215	—	—	—	SB	—	—	—
ABS	0		225	215	5.8	1.2	501—	—	—	—	—
	20		225	215	2.0	1.4	—	—	94HB	—	—
	30		230	220	1.6	1.5	—	—	94HB	19	—
	40		235	225	1.2	1.6	—	SB	94HB	—	—
Fluorocarbons ETFE	0		—	160	2.8	—	—	—	SEO	—	—
	30		—	460	1.7	—	—	NB	SEO	—	—
	FEP	0		—	0	—	—	—	94V0	95	—
25			—	220	—	—	—	94V0	95	—	
Polyamides Nylon 6	0		341	167	4.6	1.3	—	—	94V2	—	1.6
	20		420	410	2.2	2.7	951105	—	—	—	—
	30		425	420	1.7	3.3	95/105	0.44	94HB	22	—
	40		425	420	0.9	3.4	—	SB	—	—	—
Nylon 616	0		360	150	4.5	1.7	75/85	—	—	—	1.4
	20		500	485	2.3	2.9	140/—	—	94HB	21	—
	30		500	490	1.8	3.4	1401—	—	94HB	—	—
	40		500	500	1.0	3.6	—	—	—	—	—
Nylon 6110	0		300	135	5.0	1.5	—	—	94HB	25	4.2
	20		420	410	3.0	2.2	—	—	—	—	—
	30		430	420	1.5	3.5	65/—	—	94HB	—	—
	40		435	420	0.9	3.7	—	SB	—	—	—
Nylon 6/12	0		—	410	—	—	—	—	94V0	—	—
	20		—	—	—	—	—	—	—	—	—
	30		—	415	1.5	—	651120	—	94HB	—	—
	40		—	430	0.9	—	—	SB	—	—	—
Nylon 11	0		300	130	—	—	501—	—	94V2	—	—
	30		356	343	—	—	—	—	94HB	—	—
Nylon 12	0		293	130	—	—	—	—	—	—	—
	30		320	345	—	—	—	—	—	—	—
Polycarbonate	0		270	265	3.15	1.35	1151125	SE	94V1	25	0.25 ^c
	20		305	300	1.50	2.3	1201130	SE	94V1	30	0.10 ^c
	30		305	300	1.25	2.5	—	SE	94V1	30	0.08 ^c
	40		305	300	1.0	2.7	120/130	SE	94V1	29	0.07 ^c
Polyester (PBT)	0		420	—	—	—	120/140 ^d	—	94HB	—	—
	20		420	410	1.35	2.9	—	—	94HB	—	0.7 ^c
	30		440	430	1.2	3.2	1401— ^d	—	94HB	—	0.6 ^c
	40		450	450	1.05	3.5	130/—	SE	94HB	—	0.4 ^c

(continued)

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TABLE 3-9. (cont'd)

Polymer System	Glass Content, wt %	Property ASTM Method	Deflection 66 psi D648	Temp., °F 264 psi D648	Coef. of Thermal Expansion, $(\frac{\text{in.}}{\text{in.} \cdot ^\circ\text{F}}) \times 10^{-5}$ D696	Coef. of Thermal Conductivity, $\frac{\text{Btu}}{\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}/\text{in.}}$ CenCo	Maximum UL Temp Index/UL Temp index Resistance to Impact Not Essential, °C ^b UL	Flammability			Deformation Under Load 2000 psi, 24 h 50° C, % D621
								0.125 in. Specimen ASTM, in. • in./min D635	UL Subj 94	1/8 in. x 1/4 in. Specimen Oxygen index, % O ₂ D2863	
Polyether Sulfone	0		—	395	3.1	1.9	—	—	94V0	—	—
	20		—	410	2.0	2.3	—	—	94V0	—	—
	30		—	—	—	—	—	—	—	—	—
	40		—	420	1.6	2.7	—	—	94V0	—	—
Polyethylene	0		190	130	—	—	50/—	1.00	—	—	—
	20		265	250	3.0	2.4	—	—	94HB	—	—
	30		270	260	2.7	2.6	50/—	—	94HB	—	—
	40		270	260	2.4	2.8	—	—	94HB	—	—
Modified Poly-phenyleneoxide	0		279	265	3.8	1.10	901105	—	—	—	0.50
	20		295	275	1.9	1.1	501—	SE	94V1	—	—
	30		320	310	1.4	1.2	901—	—	94HB	—	—
	40		325	315	1.0	1.3	—	SE	94HB	—	—
Polyphenylene Sulfide	0		—	278	3.0	2.0	501—	—	94V0	—	—
	20		—	—	—	—	—	—	—	—	—
	30		—	500	1.1	2.8	—	—	94V0	—	—
	40		—	505	1.1	3.1	1801—	NB	94V0	—	—
Polypropylene (flame retardant)	0		250	140	—	5.0	851—	—	94HB	—	—
	20		—	265	2.4	—	1051— ^d	NB	94V0	—	—
	30		—	295	2.0	—	—	—	94HB	—	—
	40		—	300	1.7	—	—	SB	94HB	—	—
Polystyrene	0		—	195	—	—	50/—	—	94HB	—	—
	20		220	200	2.2	1.8	—	1.0	94HB	—	07
	30		230	215	1.9	2.0	—	0.9	94HB	—	04 ^e
	40		235	220	1.6	2.2	—	0.8	94HB	—	—
Polysulfone	0		358	345	3.1	1.8	140/150 ^e	—	94V1	—	—
	20		370	360	1.7	2.0	1401150 ^e	—	94V1	—	—
	30		375	365	1.4	2.2	—	—	94V1	—	—
	40		380	370	1.2	2.5	150/—	SE	94V1	—	—
SAN	0		—	190	—	—	901—	—	—	—	—
	20		220	205	2.1	1.8	—	—	94HB	—	—
	30		230	215	1.8	2.0	—	—	94HB	—	—
	40		235	220	1.5	2.2	—	SB	—	—	—
PVC	0		135	140	—	—	50/— ^d	—	94V0	—	—
	30		—	155	1.7	—	—	—	—	—	—
Polyurethane	0		—	—	—	—	—	—	—	—	—
	20		310	165	4.5	2.6	—	—	94HB	—	—
	30		315	170	2.5	2.9	—	—	94HB	—	—
	40		320	175	1.4	3.1	—	SB	94HB	—	—

^a Coefficient of thermal expansion values to be multiplied by 10⁻⁵.

^b Specimens 0.062 in. thick

^c 4000 psi, 122° C, 24 h

^d 0.03

^e 0.02

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TABLE 3-10. TENSILE STRENGTH AT ELEVATED TEMPERATURES¹

Base Resin	Glass Content, % wt	Tensile Strength, psi, at					
		73° F	200° F	300° F	350° F	400° F	450° F
Polyimide	30	13,000	6,200	4,800	3,100	2,340*	1,800
Ethylene-tetrafluoroethylene	20	11,300	6,850	4,000	2,000	*	*
Fluorinated Ethylene-propylene	20	5,000	4,200	2,300	1,200		*
Polyphenylene-sulfide	40	23,200	11,200	8,100	4,800	1,100	*
Polyethersulfone	40	22,700	19,400	13,100	4,900	3,100	*
Nylon 6/6	50	31,200	16,000	12,400	7,300	2,240*	*
Polyester	40	19,400	7,400	4,080	560	*	*
Polysulfone	40	17,300	14,900	2,300	1,100		

*No effective mechanical properties.

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TABLE 3-11. THERMOPLASTIC THERMAL ANALYSIS DATA¹¹

Base Resin	Glass Content, % wt	Melting Point T_m		Glass Transition Temperature T_g		Minor Thermal Transitions	
		°C	°F	°C	°F	°C	°F
		Nylon 6/6	50	265	509	—	—
Polyester	40	222	432	—	—	—	—
Polysulfone	40	—	—	189	374	141	281 ^b
Polyethersulfone	40	—	—	288	442	—	—
Ethylene-tetrafluoroethylene	20	272	522	—	—	—	—
Polyphenylene-sulfide	40	275	527	—	—	74	165 ^b
						112	235 ^c
Fluorinated Ethylene-propylene	20	262	504	—	—	—	—
Polyimide	30	285	545	—	—	—	—
Polytetrafluoroethylene	25	327	621 ^a	—	—	20	68
						30	86

^aSecond Melt

^bSecond-Order Transition (Endotherm)

^cFirst-Order Transition (Exotherm)

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TABLE 3-12. TENSILE

Base Resin	Glass Content, wt %	Initial Tensile Strength, psi	Strength After Aging, psi					
			100 h	250 h	500 h	750 h	1,000 h	1,500 h
Polyimide	30	13,000	13,800	13,800	13,800	13,800	13,400	13,000
Ethylene-tetrafluoroethylene	20	11,300	11,700	11,500	11,400	11,300	11,300	11,200
Fluorinated Ethylene-propylene	20	5,000	5,100	4,700	4,700	4,700	4,700	4,700
Polyphenylene-sulfide	40	23,200	23,700	23,000	22,900	20,400	18,600	16,500
Polyethersulfone	40	22,700	23,000	19,400	15,200	12,800	12,100	11,300
Nylon 6/6	50	31,000	24,200	19,500	18,600	17,200	15,600	12,000
Polyester	40	22,100	20,000	18,200	14,800	9,500	7,000	5,000
Polysulfone	40	20,300	15,000	10,000	7,800	4,300	—	—

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TABLE 3-13. TENSILE STRENGTH AFTER THERMAL AGING AT 500°F (REF. 11)

Base Resin	Glass Content, wt %	Initial Tensile Strength, psi	Strength After Aging, psi					
			100 h	250 h	500 h	750 h	1,000 h	1,500 h
Polyimide	30	13,000	15,000	14,300	13,400	12,800	12,000	11,200
Ethylene-tetrafluoroethylene	20	11,300	11,500	10,000	7,000	5,000	3,800	2,300
Polyphenylene-sulfide	40	23,200	16,400	16,000	15,500	15,000	14,500	13,800
Polyethersulfone	40	22,700	15,600	14,800	14,300	13,700	14,200	10,500
Nylon 6/6	50	31,000	17,600	10,300	9,400	—	—	—
Polyester	40	22,100	Melted	—	—	—	—	—
Polysulfone	40	20,300	Melted	—	—	—	—	—

TABLE 3-14. CHANGE IN DEFLECTION TEMPERATURE UNDER LOAD (DTUL) OF AMORPHOUS AND CRYSTALLINE POLYMERS WITH THE ADDITION OF 20% GLASS FIBER REINFORCEMENT^{1,2}

Polymers	DTUL at 264 psi stress, deg F		Increase in DTUL with glass reinforcement, deg F
	Unmodified	Glass reinforced	
Amorphous			
ABS	190	215	25
Styrene acrylonitrile	195	215	20
Polystyrene	200	220	20
Modified polyphenylene oxide	265	290	25
Polycarbonate	270	290	20
Polysulfone	345	360	15
Crystalline			
Acetal homopolymer	255	315	60
Acetal copolymer	230	325	95
Polypropylene	140	250-300	110-160
High-density polyethylene	120	260	140
Modified polypropylene ^a	140	300	160
Ethylene-propylene copolymer	120	290	170
Nylon 6/10	135	420 ^b	285
Polyethylene terephthalate	220	440	220
Nylon 6	120	425 ^b	305
Nylon 6/6	160	490 ^b	330

^a"PCO 72", product of Hercules, Inc.

^bWith 30% by weight glass reinforcement.

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TABLE 3-15. COMPARISON OF BASE POLYMER GLASS TRANSITION TEMPERATURE WITH ITS DEFLECTION TEMPERATURE UNDER LOAD (DTUL) WHEN 20% BY WEIGHT OF GLASS FIBER IS ADDED^{1,2}

Polymer	Glass-Transition Temperature of Resin, °F	Resin-Glass Composite, DTUL, °F
Polystyrene	221	220
Polyacrylonitrile	219	—
Styrene acrylonitrile	—	215
ABS	—	215
Polycarbonate	302	290
Polysulfone	374	360

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TABLE 3-16. MELTING POINTS OF CRYSTALLINE POLYMERS COMPARED WITH THEIR DEFLECTION TEMPERATURES UNDER LOAD (DTUL) WHEN GLASS FIBER REINFORCEMENT IS ADDED^{1,2}

Polymer	Melting Point of Resin, °F	Resin-Glass Composite DTUL, °F
Polyethylene-terephthalate	513	440 ^b
Polypropylene	349	300 ^b
High-density polyethylene	279	260 ^b
Acetal homopolymer	358	315 ^b
Acetal copolymer	329	325 ^b
Thermoplastic polyester ^a	437	420 ^c
Nylon 6/6	509	490 ^c
Nylon 6	437	425 ^c
Nylon 6/10	441	420 ^c
Nylon 6/12	415	410 ^c

^a"Celanex 917", product of Celanese Plastics Co.

^bWith 20% by weight glass-fiber reinforcement

^cWith 30% by weight glass-fiber reinforcement

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TABLE 3-17. FLAMMABILITY TEST METHODS²

	ASTM 0635	UL Subject 94	IBM CMH 6-0430-102	Oxygen Index Method, ASTM 02863
Test Specimen	Bar 5 in. x 1/2 in. x 1/8 in. or (1/4 in.)	Bars 6 in. x 1/2 in. x 1/16 in. and 6 in. x 1/2 in. x 1/4 in.	Bar 5 in. x 1/2 in. x 1/8 in.	Bar 7 to 15 cm long x 6.5 ± 0.5 mm wide x 3.0 ± 0.5 mm thick
Number of Specimens	10	3	5	5-10
Flame Characteristics	1 in. Height, blue flame	3/4 in. Height, blue flame	0.75 in. yellow-blue flame	6-25 mm long
Sample Position	Horizontal, longitudinal axis, transverse axis 45 deg to horizontal	Vertical	Vertical	Vertical
Position of Flame to Sample	Tip of flame contacts end of specimen	Specimen 3/8 in. above burner tube	Tip of flame contacts end of specimen. Burner may be tipped 20 deg from vertical.	Ignite top of sample
Ignition Time	30 s	10 s	5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, and 60 s	Until entire top is burning
Number of Ignitions per Sample	1	2	1	1
Procedure	Apply Bunsen burner flame to tip of specimen for 30 s	Apply Bunsen burner flame to lower tip of specimen for 10 s. If it does not ignite or stops burning before the end of a 30-s waiting period, apply again for 10 s immediately after sample has stopped glowing.	Apply Bunsen burner flame to tip of specimen for 5 s. If specimen does not ignite or stops burning before the end of a 30-s waiting period, apply Bunsen burner flame to additional specimen for 10 s, increasing flame application time in 5-s increments on fresh specimens up to 60 s.	Ignite top of specimen so that entire top is burning. Remove flame and start timer. I. The concentration of oxygen is too high and must be reduced if. (a) Specimen burns 3 min or longer, or (b) Specimen burns 5 cm. II. The concentration of oxygen must be raised if the specimen is extinguished before burning 3 min or 5 cm. Continue to adjust oxygen content until the limiting concentration is determined.
Classification	Test has been revised to eliminate "SB", "SE", and "NB" classifications. The revised specification requires the following: (a) If the bar ignites under the specified (and unchanged) application of flame and burns through the 4 in. gage length, report burning rate in. • in./min. (b) If the bar ignites but extinguishes before the flame reaches the 4 in. gage mark, report the following: ATB = average time of burning, s AEB = average extent (linear distance along the bar) of burning, in. (c) If the bar fails to ignite or extinguishes immediately after flame is withdrawn, report AEB as "less than 0.16 in." V5 = Extinguishment of flaming and glowing combustion within 60s after fifth ignition on each specimen; no dripping; no significant destruction of test specimens. HB = Burning over a 3-in. span in a horizontal bar test at a rate not more than 1.5 in./min for specimens 0.120 to 0.125 in. thick and not more than 2.5 in./min for specimens less than 0.120 in. thick; or extinguishment within a 4-in. span of materials that do not meet VO, V1, or V2 requirements.	Vertical, Group VO — — does not burn for more than 10s (an average of 5 s for 5 samples), does not burn up to the clamp, does not drip flaming particles which ignite surgical cotton, and does not glow beyond 30 s after the second flame application (10 s after first application). V1 — — does not burn for more than 30 s (an average of 25 s for 5 samples), does not burn up to clamp, does not drip and ignite cotton, and does not glow beyond 60 s after second flame application. V2 — — same as above except sample drips and ignites the cotton and, when tested in accordance with slow burning procedure, it does not burn 4 in.	Class A — — Materials which after a 60-s flame application time will extinguish within 30 s without producing flaming droplets. Class B — — Materials which after a 5-s or more flame application time will extinguish within 30 s without producing flaming droplets, but cannot withstand a 60-s flame application. Class 0 — — Materials which burn for more than 30 s or produce flaming droplets that ignite cotton after a 5-s application.	The limiting oxygen concentration is defined as that which will meet conditions I(a) above. At the next lower concentration the specimen should be extinguished as defined in II. Calculate oxygen index <i>n</i> as follows: $n = \frac{[O_2]}{[O_2] + [N_2]} \times 100, \%$ where [] indicates volumetric flow in cubic centimeters per second. The higher the oxygen index of a material, the greater the flammability resistance. The notation "> 100" means simply that the specimen would not continue to burn after ignition in 100% oxygen or that it could not be ignited by the specified gas flame.

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TABLE 3-18. ELECTRICAL PROPERTIES OF GLASS-REINFORCED THERMOPLASTICS

Polymer System	Glass Content, wt%	Volume Resistivity, ohm-cm	Dielectric Strength 1/8 in., S/T, V/m D 149	Arc Resistance, s	Dielectric Constant 60-10 ⁶ Hz, dimensionless 0150	Dissipation Factor 60-10 ⁶ Hz, dimensionless D 150	Surface Resistivity, ohm 0257	
Acetal	0	1.0 x 10 ¹⁴	500	240	3.7-3.7	0.0010-0.006	-	
	20	1.2 x 10 ¹⁶	525	160	3.95-3.95	0.0035-0.0065	-	
	30	2 x 10 ¹⁶	525	-	3.95-3.95	0.0035-0.0065	-	
	40	-	525	-	-	-	-	
Acrylic	0	> 10 ¹⁴	400-500	-	(3.3-3.9)-(2.2-3.2)	(0.04-0.06)-(0.02-0.03)	-	
	30	-	-	-	-	-	-	
ABS -- General purpose	0	2.7 x 10 ¹⁶	350-500	50-85	(2.4-5.0)-(2.4-3.8)	(0.003-0.008)-(0.007-0.015)	-	
	20	10 ¹⁵	480	65	3.2-3.2	0.006-0.007	10 ¹⁶	
	30	10 ¹⁵	-	-	-	-	-	
	40	10 ¹⁵	-	-	-	-	-	
Fluorocarbons ETFE	0	> 10 ¹⁶	400	72	2.6-2.6	0.008-0.005 ^a	-	
	30	-	410	-	3.6-3.6	0.004-0.005	-	
FEP	0	> 10 ¹⁸	-	-	2.10-2.10	0.0005-0.0005	> 10 ¹⁶	
	25	2 x 10 ¹⁵	415	180	2.55-2.52	0.002-0.002	-	
Polyamides ^b --6 (nylons)	0	10 ¹¹	400	-	3.8-3.4	0.01-0.03	-	
	20	-	-	-	-	-	-	
	30	2.8 x 10 ¹⁴	450	135	4.20-3.60	0.009-0.018	-	
	40	10 ¹⁴	580	90	4.4-4.0	0.020-0.021	-	
	--616	0	10 ¹¹ -10 ¹⁴	600	130-140	4.3 (60 Hz)	0.020-0.04	-
		20	> 10 ¹⁵	-	-	4.2-3.5	0.01-0.01	-
		30	5.0 x 10 ¹⁴	440	130	4.20-3.50	0.009-0.0180	-
		40	10 ¹⁵	480	100	4.4-4.1	0.009-0.018	-
	--6/10	0	10 ¹²	400	-	3.9-3.5	0.04-0.04	-
		20	-	-	-	-	-	-
		30	7.6 x 10 ¹⁵	440	125	4.20-3.50	0.013-0.015	-
		40	10 ¹⁵	500	-	4.2-4.0	0.013-0.016	-
	--6112	0	10 ¹³	400	-	3.9-3.5	0.02-0.02	-
		20	-	-	-	-	-	-
		30	10 ¹²	440	-	4.20-3.50	0.013-0.015	-
		40	-	-	-	-	-	-
--11	0	10 ¹³	425	-	3.7-3.2 ^b	-	-	
	30	10 ¹⁴	500	-	-	-	-	
--12	0	10 ¹³	450	110	4.2-3.1	0.04-0.03	-	
	30	10 ¹³	452	-	3.0 (10 ⁶ Hz)	0.06 (10 ⁶ Hz)	-	
Polycarbonates	0	2.1 x 10 ¹⁶	380	-	2.97-2.92	0.009-0.010	-	
	20	1.5 x 10 ¹⁵	475	-	3.7-3.3	0.0060-0.009	7 x 10 ¹⁵	
	30	6.0 x 10 ¹⁵	480	120	3.50-3.43	0.0010-0.0075	-	
	40	1.5 x 10 ¹⁵	482	-	3.8-3.7	0.003-0.008	7 x 10 ¹⁵	
Polyester	0	10 ¹⁵ -(2 x 10 ¹⁶)	420-556	75-192	3.29-3.1	0.0014-0.022 ^a	-	
	20	-	-	-	-	-	-	
	30	2.7 x 10 ¹⁵	510	-	3.60-2.00	0.002-0.020	-	
	40	-	-	-	-	-	-	
Polyethersulfone	0	10 ¹⁷ -10 ¹⁸	400	-	3.50-3.50	0.001-0.006	-	
	20	-	-	-	-	-	-	
	30	-	460	-	3.80-3.76	0.002-0.005	-	
	40	-	-	-	-	-	-	
Polyethylene	0	> 10 ¹⁶	450-500	-	2.30-2.30	< 0.0005-< 0.0005	-	
	20	10 ¹⁵	700	130	2.6-2.6	0.001-0.001	10 ¹⁵	
	30	-	-	-	-	-	-	
	40	10 ¹⁶	600	120	2.9-2.8	0.001-0.001	10 ¹⁶	
Modified Polyphenylene Oxide	0	1.0 x 10 ¹⁷	550	75	2.65-2.64	0.0004-0.0009	-	
	20	1.0 x 10 ¹⁷	420	70	2.86-2.85	0.0008-0.0014	-	
	30	1.0 x 10 ¹⁷	550	120	2.90-2.90	0.001-0.0015	-	
	40	-	-	-	-	-	-	

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TABLE 3-18. (cont'd)

Polymer System	Glass Content, wt %	Volume Resistivity, ohm-cm	Dielectric Strength 1/8 in., S/T, V/m D149	Arc Resistance, s	Dielectric Constant 60–10 ⁶ Hz, dimensionless D150	Dissipation Factor 60–10 ⁶ Hz, dimensionless D150	Surface Resistivity, ohm D257
Polyphenylene Sulfide	0	10 ¹⁶	595	—	3.11–3.22 ^b	0.0004–0.0007 ^b	—
	20	—	—	—	—	—	—
	30	—	510	—	3.88–3.78	0.003–0.007	—
	40	4.5 x 10 ¹⁶	350	—	3.9–3.8'	0.0010–0.0013'	—
Polypropylene	0	>10 ¹⁶	500–660	—	(2.2–2.6)–(2.2–2.6)	<0.0005–0.0005	—
	20	2 x 10 ¹⁶	475	100	2.30–2.20	0.0004–0.0020	10 ¹⁷
	30	2 x 10 ¹⁶	475	—	2.30–2.20	0.001–0.003	—
	40	10 ¹⁶	300	70	2.5–2.5	0.002–0.003	10 ¹⁷
Polystyrene	0	>10 ¹⁶	500–700	60–140	(2.45–3.1)–(2.40–2.7)	0.0001–0.0006)–(0.0001–0.0004)	—
	20	10 ¹⁶	412	40	2.8–2.8	0.0005–0.0005	—
	30	3.5 x 10 ¹⁶	550	100	2.81–2.81	0.0007–0.0008	—
	40	—	—	—	—	—	—
Polysulfone	0	5.0 x 10 ¹⁶	425	75–122	3.07–3.14)–(3.03–3.10	0.0008–0.0034	—
	20	>10 ¹⁶	—	—	3.3 (50–100Hz)	0.0068 (50–100Hz)	—
	30	1.0 x 10 ¹⁷	480	115	3.55–3.49	0.0019–0.0049	—
	40	—	—	—	—	—	—
Polyurethane	0	(2.0 x 10 ¹¹)–(0.11 x 10 ¹⁴)	330–630	122	(5.4–7.6)–(4.21–5.10)	(0.015–0.048)–(0.050–0.100)	—
	20	—	—	—	—	—	—
	30	—	—	—	—	—	—
	40	—	—	—	—	—	—
PVC	0	>10 ¹⁶	300–500	60–80	(3.2–4.0)–(2.8–3.1)	(0.007–0.020)–(0.006–0.019)	—
	15	—	450	—	3.78–3.42	0.009–0.016	—
	25	1.0 x 10 ¹⁶	450	90	3.78–3.42	0.009–0.016	—
SAN	0	>10 ¹⁶	400–500	100–150	(2.6–3.4)–(2.6–3.1)	(0.0006–0.008)–(0.007–0.010)	—
	20	—	—	—	—	—	—
	30	1.0 x 10 ¹⁶	450	120	2.83–2.77	0.0020–0.0300	—

^a at 10³–10⁶ Hz^b dry as molded

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TABLE 3-19. CHEMICAL RESISTANCE OF REINFORCED RESINS AT ROOM TEMPERATURE²

Base Resin	Glass Filler, wt% vol %		Initial Tensile Strength, psi	Hydrochloric Acid, 10%	Sulfuric Acid, 10%	Acetic Acid	Ammonium Hydroxide	Heptane	Ethylene Glycol	Methanol	Gasoline	Motor Oil	Brake Fluid
ABS	30	14.9	19,000	F 11 16,100 F 7 16,660	A 4 17,960 F 10 15,300	A 5 17,880 F 11 14,820	F 7 15,560 X 12 11,340	F 9 17,920 A 10 17,540	E 8 19,080 A 10 18,070	X 14 13,360 X 16 7,600	X 16 5,950 X 15 5,150	F 10 17,020 F 13 16,660	X 17 10,130 X 16 1,250
SAN	30	15.4	17,400	F 9 14,830 F 11 13,730	F 6 15,260 F 9 14,080	F 11 14,230 F 11 13,570	X 11 12,700 F 7 13,570	E 3 17,570 E 6 17,170	E 3 18,240 F 14 15,420	X 18 3,240 X 18 2,630	X 12 13,000 X 16 D	X 18 12,950 F 15 14,340	X 18 6,070 X 17 D
Polystyrene	30	15.0	12,500	F 13 10,350 X 13 8,460	X 14 8,830 X 13 8,460	X 15 8,710 X 14 7,530	X 12 6,930 X 11 7,930	A 9 1,780 X 17 D	A 14 11,490 F 17 9,950	X 16 7,230 X 17 3,240	X 17 D X 16 D	F 14 10,530 X 18 6,400	X 19 10,050
Polycarbonate	30	16.8	18,500	A 5 17,560 A 5 17,460	F 9 16,130 A 4 16,800	A 8 17,060 A 5 16,760	X 15 9,030 X 16 8,230	A 12 16,890 A 7 17,820	E 9 18,540 F 16 14,780	F 9 15,950 F 10 16,480	F 9 15,060 F 8 14,710	F 15 15,370 F 17 14,760	F 14 14,100 X 12 13,320
	0	0	8,300	A 4 7,890 A 6 7,820	A 3 7,860 F 6 6,920	A 6 7,690 A 6 7,480	X 17 2,570 X 17 2,570	F 14 7,370 A 9 7,820	F 15 7,310 A 11 7,870	A 7 7,710 A 7 7,610	F 8 6,800 X 10 5,940	F 12 7,200 F 14 7,180	F 11 6,670 X 14 2,820
Polyethylene	30	13.9	10,000	F 11 8,470 F 8 8,240	F 10 8,490 F 8 8,220	F 13 7,920 F 9 7,850	X 16 4,670 X 15 4,580	F 16 8,150 X 15 6,430	E 12 9,710 A 9 9,660	A 6 9,330 F 9 8,960	F 11 7,510 X 9 7,370	E 4 9,780 E 6 9,710	A 6 9,820
Polysulfone	30	17.3	18,000	F 8 15,880 X 14 11,680	F 7 15,750 F 11 13,730	A 9 16,220 F 7 14,400	F 10 13,930 F 9 13,820	A 8 17,460 A 12 16,520	E 7 18,200 E 7 17,780	A 8 16,380 A 6 16,580	X 14 8,100 X 14 7,940	E 5 17,510 E 4 17,950	X 15 13,410 X 13 12,710
Polyacetal	30	19.2	13,000	F 14 10,750 F 12 10,100	F 13 10,050 X 14 7,900	F 10 10,860 F 13 10,100	F 9 10,210 X 10 9,450	E 2 13,160 A 8 12,260	F 16 11,350 A 12 12,300	F 10 10,560 F 11 9,750	E 2 13,000 E 2 12,950	E 1 14,000 E 1 13,900	E 1 13,900 E 3 13,100
	0	0	8,200	E 2 8,200 E 1 8,130	X 18 3,610 X 15 4,690	E 1 7,870 E 1 8,170	E 1 8,220 E 1 8,260	E 1 8,270 E 1 8,160	E 4 8,310 E 2 8,290	E 4 7,840 E 4 7,870	E 1 8,210 E 1 8,210	E 2 8,420 E 3 8,380	E 2 8,390 E 1 8,340
Polypropylene	30	13.2	7,800	A 5 7,400 F 8 6,840	A 5 7,320 A 3 7,320	A 4 7,430 A 6 7,030	A 4 7,300 A 4 6,990	X 18 3,500 X 16 3,530	E 2 8,280 E 4 7,900	E 1 7,820 A 5 7,340	X 15 6,500 A 3 6,730	A 7 7,070 A 7 7,210	A 5 7,540 E 2 7,980
Nylon 6	30	16.1	23,000	X 18 9,360 X 17 11,780	X 17 10,630 X 18 10,510	X 18 11,250 X 17 10,880	X 14 11,640 X 14 11,730	A 9 21,690 E 5 22,750	E 10 22,560 E 6 22,770	F 11 17,730 E 3 22,950	F 7 19,160 F 6 19,850	A 9 20,840 A 8 21,250	A 5 22,800
Nylon 6/10	30	15.4	21,000	F 15 17,070 F 10 16,840	F 11 16,860 F 7 17,330	F 14 16,360 F 10 16,420	F 8 16,720 F 8 16,360	E 3 21,210 E 3 21,020	E 10 20,600 E 8 20,660	X 12 14,950 X 12 14,910	F 6 17,810 F 7 17,640	F 11 18,440 F 12 18,540	A 8 19,450 A 8 19,380
Nylon 6/6	30	16.1	26,000	X 17 14,200 X 16 14,430	X 16 14,510 X 16 14,980	X 17 14,200 X 16 14,200	X 13 13,570 X 13 13,620	A 13 23,530 F 13 23,060	F 17 21,090 F 15 22,200	X 13 18,300 X 13 17,680	F 5 22,850 X 11 18,490	F 16 20,930 A 11 23,580	F 13 19,990 A 7 24,050
	0	0	11,800	X 16 7,820 X 15 7,620	X 15 7,710 X 17 6,400	X 16 7,580 X 14 7,290	X 18 2,500 X 18 2,500	X 17 8,370 F 14 8,970	X 18 7,120 X 18 7,670	X 15 7,520 X 14 7,410	F 10 9,350 X 12 8,250	F 17 9,160 A 9 10,740	F 10 9,750 A 9 10,670
Thermoplastic Polyurethane	30	17.4	8,200	F 10 6,960 F 9 6,720	F 8 7,170 F 5 6,940	F 12 6,630 F 8 6,500	F 6 6,900 F 6 6,450	E 3 8,280 E 2 8,330	E 1 8,850 E 1 8,630	X 17 4,070 X 15 4,140	X 13 4,170 X 13 5,640	F 13 6,910 F 16 6,610	X 16 5,050 X 15 2,410
PVC	15	9.1	16,000	E 3 15,840 E 3 15,860	E 1 15,900 E 1 15,700	A 2 15,490 A 2 15,490	E 3 15,540 E 3 15,570	E 7 15,840 E 4 15,840	E 6 16,220 E 3 16,300	E 3 15,810 E 1 16,000	F 4 14,400 F 5 14,210	A 8 14,780 A 9 14,560	F 12 12,750 F 10 13,170
Thermoplastic Polyester	30	18.8	19,500	A 7 17,860 A 4 18,450	F 12 15,420 F 12 14,780	A 7 18,040 A 4 17,920	F 5 17,060 F 5 16,670	E 6 19,680 E 2 19,810	A 13 18,040 F 13 17,470	E 5 18,720 A 8 17,760	A 3 17,800 A 4 17,800	E 6 18,950 E 5 19,210	E 3 19,680 A 4 18,780
Modified PPO	30	15.2	21,000	E 1 21,740 E 2 21,150	A 2 20,310 A 2 19,760	A 3 20,200 A 3 19,760	E 2 21,570 E 2 21,210	F 15 17,620 A 11 19,320	E 5 21,800 E 5 21,190	E 2 20,850 E 1 21,000	X 17 D X 16 D	E 3 21,150 E 2 22,050	E 4 20,850 F 11 16,800

The three columns under each chemical listed consist of: 1. A letter-grade, ranking the resistance of the material to the chemical. (See key below.) 2. A numerical ranking of the material/chemical combination, based on the materials tested. (Number 1 in each column has the highest resistance to the specific chemical.) 3. Tensile strength of the material (psi) tested after exposure to the chemical for seven days at room temperature.

Values in light type are for unstrained samples; values shown in bold type are for materials exposed to the chemicals under an applied strain, in flexure, of ¼%.

E = Excellent: 0 to 3% loss of tensile strength. X = Unacceptable: more than 25% loss of tensile strength.
A = Acceptable: 3 to 10% loss of tensile strength. C = Sample crazed or cracked.
F = Fair: 10 to 25% loss of tensile strength. D = Sample dissolved or severely tackified.

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TABLE 3-20. CHEMICAL RESISTANCE AT ELEVATED TEMPERATURE*

Base Polymer	TENSILE STRENGTH AFTER EXPOSURE FOR 72h AT 180° F (82° C), psi																	
	Hydrochloric Acid, 10%		Ammonia Hydroxide+, 10%		Ethylene Glycol		Methanol		Gasoline		Motor Oil		Brake Fluid		Carbon Tetrachloride		Benzene	
ABS	F 7	15,220	X 6	13,410	F 7	16,850	X 9	13,360	X 11	6,050	F 12	15,470	X 10	C	X 11	C	X 8	D
Polystyrene	F 8	9,850	X 9	5,010	F 9	10,690	X 13	2,760	X 12	D	F 9	10,580	X 10	D	X 11	C	X 8	D
Poly carbonate	F 3	16,510	X 12	C	A 4	17,460	X 8	13,130	F 5	15,800	E 3	17,950	X 10	C	F 6	13,890	X 8	C
Nonreinforced Polycarbonate	A 2	7,690	X 12	C	F 8	7,290	F 5	7,010	X 9	5,830	A 5	7,810	X 10	C	X 7	5,330	X 8	D
Polyethylene	F 6	8,190	X 7	5,820	A 6	9,240	F 3	8,720	X 7	7,160	A 6	9,040	A 3	9,160	X 8	5,760	F 5	7,540
Polysulfone	F 5	14,770	F 5	14,010	E 3	18,020	F 4	15,680	X 8	12,730	E 2	17,740	X 9	13,170	X 9	9,620	X 8	D
Polyacetal	X 11	C	F 4	10,200	F 10	10,800	F 7	9,900	F 3	11,500	F 8	11,300	F 6	10,450	F 5	11,500	X 6	7,750
Unreinforced Polyacetal	X 11	C	E 1	8,570	E 2	8,460	E 1	8,200	E 1	8,280	E 1	8,200	E 2	8,200	E 1	8,230	E 1	8,200
Polypropylene	F 4	6,440	F 3	6,990	A 5	7,280	F 6	6,450	X 10	4,570	F 13	6,300	A 4	6,760	X 10	3,490	X 7	4,620
Nylon 6/10	X 9	8,850	X 8	9,270	X 11	15,230	X 10	12,340	A 2	19,740	A 4	20,150	A 5	17,120	E 2	21,000	A 2	19,380
Nylon 6/6	X 10	1,850	X 10	8,450	X 12	15,210	X 11	12,700	F 6	22,200	F 10	21,750	F 7	19,500	A 4	25,025	F 3	23,170
Unreinforced Nylon 6/6	X 11	C	X 11	2,510	X 13	4,370	X 12	4,650	F 4	10,250	F 11	9,620	X 8	8,780	E 2	11,800	F 4	10,440
Modified PPO	E 1	21,000	A 2	19,250	E 1	21,840	E 2	20,440	X 12	D	A 7	18,940	E 1	21,210	X 11	D	X 8	D

The three columns under each chemical listed consist of: 1. A letter-grade, ranking the resistance of the material to the chemical. (See key below.) 2. A numerical ranking of the material/chemical combination, based on the materials tested. (Number 1 in each column has the highest resistance to the specific chemical.) 3. Tensile strength of the material (psi) tested after exposure to the chemical.

Key:

E = Excellent: 0 to 3% tensile loss on exposure.
 A = Acceptable: 3 to 10% tensile loss on exposure.
 F = Fair: 10 to 25% tensile loss on exposure.

X = Unacceptable: >25% tensile loss on exposure.
 C = Sample experienced crazing or cracking on exposure.
 D = Sample dissolved or severely tackified on exposure.
 * = Test Temperature 65° C.

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TABLE 3-21. CHEMICAL RESISTANCE AT ROOM TEMPERATURE²

Base Resin	WEIGHT GAIN AFTER EXPOSURE FOR 7 DAYS AT 70° F (21° C), %													
	Glass Filler, wt%	Glass Filler, vol %	Hydrochloric Acid, 10%	Sulfuric Acid, 10%	Acetic Acid, 10%	Ammonia Hydroxide, 10%	Heptane	Ethylene Glycol	Methanol	Gasoline	Motor Oil	Brake Fluid	Dimethyl-sulfoxide	Benzene
ABS	30.00	14.90	0.03	0.06	0.25	0.27	0.07	-0.13	0.41	0.19	0.07	0.19	D	D
SAN	30.00	15.40	0.33	0.31	0.42	0.47	-0.02	0.04	9.37	0.04	0.11	0.11	D	D
Polystyrene	30.00	15.03	0.13	0.18	0.28	0.25	0.57	0.08	1.63	D	0.07	0.31	D	D
Polycarbonate	30.00	16.80	0.14	0.17	0.22	-12.76	0.45	0.58	0.75	0.26	0.02	0.05	C	C
Polycarbonate	0.00	0.00	0.18	0.11	0.28	-16.60	0.21	0.01	1.67	0.26	0.01	0.13	C	D
Polyethylene	30.00	13.93	-0.12	0.13	0.05	0.33	2.80	0.07	0.05	1.61	0.66	0.12	0.31	0.23
Polysulfone	30.00	17.30	0.26	0.28	0.34	0.36	0.45	-0.03	0.82	0.14	0.08	0.68	D	D
Polyacetal	30.00	19.20	0.12	0.18	0.25	0.34	0.16	0.17	0.75	0.21	0.12	0.33	1.19	0.06
Polyacetal	0.00	0.00	0.24	0.25	0.31	0.31	0.22	0.26	0.73	0.29	0.25	0.46	0.64	0.17
Polypropylene	30.00	13.20	0.03	0.10	0.08	0.11	4.83	0.21	0.12	4.64	0.25	0.15	0.64	0.23
Nylon 6	30.00	16.10	3.78	5.71	4.37	3.59	0.21	1.34	6.98	0.21	0.64	0.11	0.61	1.39
Nylon 6/10	30.00	15.40	0.95	1.17	1.13	0.91	0.07	0.59	4.90	0.09	0.00	0.10	1.18	0.30
Nylon 6/6	30.00	16.10	2.49	3.21	2.65	2.47	0.18	0.80	3.11	0.15	0.05	0.16	0.41	0.33
Nylon 6/6	0.00	0.00	5.18	5.11	5.54	5.17	1.48	1.84	7.14	1.20	0.15	0.19	2.29	0.30
Thermoplastic Polyurethane	30.00	17.40	0.02	0.02	0.65	0.64	0.31	0.01	0.24	0.23	0.04	0.08	0.18	0.12
PVC	25.00	15.10	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.15	0.11	C	D
Thermoplastic Polyester	30.00	18.76	0.37	0.38	0.21	0.25	0.09	0.01	0.28	0.08	0.01	0.16	3.38	0.05
Modified PPO	30.00	15.20	0.02	0.01	0.11	0.19	0.54	0.23	0.83	1.02	0.32	0.23	0.28	D

Code: D = dissolved
C = cracked

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TABLE 3-22. EFFECT OF WEATHERING ON IMPACT STRENGTH OF UV-STABILIZED GLASS-REINFORCED THERMOPLASTICS~

Base Resin*	Impact Strength, ft•lb/in.																	
	Initial		3 Months				6 Months				12 Months				24 Months			
			Notched		Unnotched		Notched		Unnotched		Notched		Unnotched		Notched		Unnotched	
	Notched	Unnotched	Phila.	L.A.	Phila.	L.A.	Phila.	L.A.	Phila.	L.A.	Phila.	L.A.	Phila.	L.A.	Phila.	L.A.	Phila.	L.A.
Polystyrene	0.9	2.4	0.9	1.1	2.3	2.0	0.9	0.9	2.1	2.0	1.0	0.9	2.4	2.2	1.0	1.0	2.0	2.0
Polycarbonate	1.8	13.0	1.7	1.7	10.4	10.8	1.5	1.5	9.6	9.4	1.4	1.5	9.1	9.6	1.4	1.5	8.4	8.4
Polyethylene	1.4	6.6	1.4	1.4	5.7	5.9	1.3	1.3	5.6	5.5	1.3	1.4	5.3	5.0	1.3	1.5	5.3	4.8
Polysulfone	1.1	5.1	1.1	1.1	5.0	5.1	1.0	1.0	4.6	4.5	1.1	1.1	5.2	5.0	1.1	1.1	5.0	4.8
Polypropylene	1.1	2.4	1.0	1.1	2.9	2.6	1.1	1.1	2.8	2.5	1.1	1.1	3.0	3.2	1.1	1.1	3.0	2.8
Nylon 6	1.8	11.5	1.8	1.9	10.6	11.4	1.7	1.8	13.2	13.8	1.9	1.9	14.3	15.4	1.9	1.9	14.0	15.0
Nylon 6/10	1.8	10.6	1.7	1.6	9.1	11.0	1.7	1.5	10.3	11.3	1.5	1.5	11.6	11.3	1.5	1.6	11.6	11.0
Nylon 6/6	1.6	10.7	1.7	1.8	8.8	10.5	1.7	1.7	14.8	9.4	1.7	1.6	14.5	14.5	1.4	1.8	14.9	14.5
PVC	0.8	8.1	0.8	0.9	8.1	6.7	0.8	0.8	8.2	7.4	1.0	0.9	5.8	5.2	1.0	0.9	5.2	6.0
Thermoplastic Polyester	1.4	8.6	1.3	1.5	8.2	7.4	1.2	1.3	9.2	8.1	1.2	1.2	7.2	7.9	1.2	1.4	7.0	8.6

*All are 30% glass-reinforced except PVC which contains 15% glass; all contain 1% carbon black.

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TABLE 3-23. EFFECT OF WEATHERING ON TENSILE STRENGTH OF UV-STABILIZED GLASS-REINFORCED THERMOPLASTICS*

Base Resin**	Tensile Strength, psi								
	Initial	3 Months		6 Months		12 Months		24 Months	
		Phila.	L.A.	Phila.	L.A.	Phila.	L.A.	Phila.	L.A.
Polystyrene	13,600	11,700	12,350	11,950	11,600	12,750	12,100	11,600	12,400
Polycarbonate	19,470	17,200	17,500	16,830	17,600	17,370	17,270	17,300	17,000
Polyethylene	9,500	8,980	9,300	9,020	9,390	9,670	9,270	10,000	9,900
Polysulfone	14,360	13,050	13,750	13,660	13,530	13,180	13,670	13,000	13,600
Polypropylene	7,600	7,100	7,500	7,180	7,630	8,100	8,000	8,100	8,000
Nylon 6	18,000 [†]	18,560	18,900	8,320	18,300	18,100	18,120	18,000	18,300
Nylon 6/10	20,000 [†]	17,300	17,920	6,300	18,070	18,000	18,230	18,700	19,300
Nylon 6/6	5,000 [†]	16,780	17,330	5,630	16,020	5,450	16,050	15,100	16,800
PVC	5,170	14,700	15,170	14,760	15,050	5,800	15,570	16,300	15,500
Thermoplastic Polyester	9,210	17,780	18,700	18,000	18,500	8,370	18,600	19,300	19,800

*All are 30% glass-reinforced except PVC which contains 15% glass.

[†]Moisture conditioned at 50% relative humidity.

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TABLE 3-24. PHYSICAL AND MECHANICAL PROPERTIES OF ACETALS

Glass Content	ASTM Test Method	Non-reinforced Acetal	THERMOCOMP					CELCON		FORMALDAFIL						THERMOFIL				FIBERITE RTP		
			KFX-1002 10%	KF-1006 30%	KFX-1006 30% Chem. Coupled	KFX-1008MG 40%	KF-1008B 40%	CR20 20%	GC25 25% Chem. Coupled	G80/20 ^a 20%	G80/30 ^a 30%	G80/40 ^a 40%	J80/20 ^b 20%	J80/30 ^b 30%	J80/40 ^b 40%	62000 20%	63000 30%	G3020 30% TFE	63020 30% TFE	803 20%	805 30%	807 40%
	0792	1.41	1.47	1.63	1.63	1.71	1.71	—	1.61	1.55	1.62	1.69	1.55	1.62	1.69	1.54	1.63	1.65	1.65	1.55	1.63	1.74
	D792	19.7	18.9	17.0	17.0	16.2	16.2	—	17.4	—	—	—	—	—	—	—	—	—	—	—	—	—
	D570	0.22	0.24	0.60	0.30	0.50	0.45	—	0.29	0.45	0.70	0.80	0.5	0.7	1.0	—	—	—	—	0.5	0.9	1.0
		0.022	0.008	0.005	0.003	0.006	0.013	—	0.004	0.008'	0.006'	0.006'	0.006'	0.006'	0.006'	—	—	—	—	0.006	0.004	0.003
		0.018	0.010	0.017	0.016	0.008	0.011	—	0.018	—	—	—	—	—	—	—	—	—	—	—	—	—
	0638	8,800	12,500	13,000	19,500	13,500	6,000	11,000	18,500	11,000	11,000	11,500	9,000	9,500	10,000	6,000 ^d	12,600 ^d	13,000 ^d	8,000 ^d	12,000	12,500	13,000
	0638	410,000	—	—	—	—	—	1,000,000	1,250,000	1,000,000	1,200,000	1,400,000	1,000,000	1,200,000	1,400,000	—	—	—	—	1,200,000	1,400,000	1,600,000
	01822	70	—	—	—	—	—	25	50	—	—	—	—	—	—	—	—	—	—	—	—	—
	D638	60	—	—	—	—	—	2	3	23	2.1	2.0	2.2	1.5	1.0	3	2	3	2	22	1.6	1.5
	D638	10.0	6.0	2.0	3-4	3.0	5-6	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0790	13,000	18,500	17,500	29,000	21,000	11,500	16,000	28,000	15,000	15,000	15,000	11,500	12,000	12,500	—	—	—	—	16,500	16,800	17,000
	D790	375,000	550,000	1,300,000	1,400,000	1,100,000	600,000	920,000	1,100,000	800,000	1,000,000	1,200,000	700,000	1,000,000	1,200,000	910,000	1,200,000	780,000	750,000	900,000	1,100,000	1,300,000
	0732	7,700	8,000	8,200	9,000	8,200	6,000	—	13,000	8,000	8,500	9,000	—	—	—	—	—	—	—	—	—	—
	D256																					
		13	14	0.8	1.8	1.1	0.7	0.8	1.8	28	2.8	2.8	0.8	0.8	0.9	0.8	0.8	1.0	0.5	0.9	0.9	0.9
		20.0	10.0	3-4	8-10	6-7	3-4	4.0	8.2	—	—	—	—	—	—	—	—	—	—	7.0	5.0	4.0
	D785	M80	M82	M86	M86	M84	M84	—	—	M75-85	M75-85	M75-85	M75-85	M75-85	M75-85	—	—	—	—	107	112	118
	D695	—	—	—	—	—	—	—	—	12,000	12,000	11,000	—	—	—	—	—	—	—	12,000	11,500	11,000

^a G = 1/8 in. dia X 3/8 in. long glass fiber

^b J = 1/8 in. dia X 1/8 in. or 1/4 in. long glass fiber

^c 112 in. ave. section from laboratory specimens; direction of flow unknown

^d Tensile strength at yield at 1,000 psi

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LNP Series Code	PTFE Lubricant, wt %	Glass Content, wt %	Limiting PV (Journal Half Bearing)		
			10 ft/min	100 ft/min	1,000 ft/min
K 1000	—	—	4,000	3,500	< 2,500
Fulton 404	20	—	10,000	12,500	5,500
KFL 4036	15	30	12,500	12,000	8,000

TABLE 3-26. WEAR AND FRICTIONAL PROPERTIES OF ACETAL¹⁴

LNP Series Code	PTFE Lubricant, wt %	Glass Content, wt %	K-factor, ^a $\frac{(\text{in}^3 \cdot \text{min})}{(\text{ft} \cdot \text{lb} \cdot \text{oh})} \times 10^{-10}$	Coefficient of Friction	
				Static (40 psi)	Dynamic (40 psi, 50 ft/min)
K 1000	—	—	65	0.14	0.21
KL 4010	5	—	40	0.12	0.18
KL 4020	10	—	30	0.10	0.17
KL 4015	15	—	20	0.07	0.15
Fulton 404	20	—	17	0.07	0.15
KFL 4036	15	30	200	0.20	0.28

^aK-factor values to be multiplied by 10^{-10} .

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TABLE 3-27. THERMAL PROPERTIES OF ACETALS

Property	Glass Content ASTM Test Method	Non-reinforced Acetal	THERMOCOMP					CELCON		FORMALDAFIL						THERMOFIL				FIBERITE RTP		
			KF-1002 10%	KF-1006 30%	KFX-1006 30% Chem. Coupled	KFX-1008MG 40%	KF-1008B 40%	CR20 20%	GC25 25% Chem. Coupled	G80/20 ^a 20%	G80/30 ^a 30%	G80/40 ^a 40%	J80/20 ^b 20%	J80/30 ^b 30%	J80/40 ^b 40%	G2000FG 20%	G3000FG 30%	G3020FG 30%, TFE	G3020MG 30%, TFE	RTP803 20%	RTP805 30%	RTP807 40%
Crystalline Melting Point, °F °C	-	329	-	-	-	-	-	-	331	-	-	-	-	-	-	-	-	-	-	-	-	-
		165	-	-	-	-	-	-	166	-	-	-	-	-	-	-	-	-	-	-	-	-
Vicat Softening Point, °F	-	324	-	-	-	-	-	-	324	-	-	-	-	-	-	-	-	-	-	-	-	-
Deformation Deflection Temperature, °F 264 psi 66 psi	0648	230	300	325	330	310	250	-	325	325	325	325	320	320	320	320	325	325	310	325	325	328
		316	-	-	-	-	-	-	331	325	325	325	325	325	325	-	-	-	-	330	330	332
Deformation Under Load, 2000 psi, 24 h, 50° C, %	0621	1.0	0.85	0.65	0.60	0.80	0.85	0.6	1.5'	1.5 ^c	1.4 ^c	-	-	-	-	-	-	-	-	-	-	
Coefficient of Linear Thermal Expansion, (in./in.·°F) x 10 ⁻⁴	0696	4.7	2.6	2.4	2.2	2.4	3.0	2.2	3.5	-	1.9	-	-	-	-	-	-	-	2.5	2.3	1.8	
Flammability	UL Subj. 94	94HB	94HB	94HB	94HB	94HB	94HB	-	-	-	-	-	-	-	-	-	-	-	-	HB	HB	HB
Flammability	0635	1.1	-	-	-	-	-	1.0	-	-	-	-	-	-	2.1	1.8	.0	-	B	B	B	
Thermal Conductivity, Btu/h·ft ² ·°F/in.	C-177	1.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.0	2.2	2.3	

^a G = 1/8 in. dia x 3/8 in. long glass fiber
^b J = 1/8 in. dia x 1/8 in. or 1/4 in. long glass fiber
^c at 4000 psi, 122° F

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TABLE 3-28. ELECTRICAL PROPERTIES OF ACETALS

Property	ASTM Test Method	Non-reinforced Homopolymer	Non-reinforced Copolymer	CELCON	FORMALDAFIL	THERMOFIL			FIBERITE RTP		
				GC25, 25% (73° F, 50% RH)	G80/40 40%	G2000 20%	G3000 30%	G3020 30% TFE	803 20%	805 30%	807 40%
Dielectric Strength, V/mil (short time in oil)	D149	380	500	580	—	500	520	500	500	500	500
Dielectric Constant, dimensionless	D150										
10 ² Hz		—	—	3.9	—	—	—	—	—	—	—
10 ³ Hz		3.7	3.7	3.9	—	—	—	—	—	—	—
10 ⁴ Hz		—	—	3.9	—	—	—	—	—	—	—
10 ⁶ Hz		3.7	3.7	3.9	—	—	—	—	4.0	4.0	4.0
Dissipation (Power) Factor, dimensionless	D150										
10 ² Hz		—	—	0.0027	—	—	—	—	—	—	—
10 ³ Hz		—	—	0.0025	—	—	—	—	—	—	—
10 ⁴ Hz		0.0048	0.0010	0.0025	—	—	—	—	—	—	—
10 ⁶ Hz		0.0048	0.006	0.0062	—	—	—	—	0.0055	0.0055	0.0055
Surface Resistivity, ohm	D257	—	—	3.8 x 10 ¹⁵	10 ¹⁶	—	—	—	—	—	—
Volume Resistivity, ohmcm	D257	1.0 x 10 ¹⁵	1.0 x 10 ¹⁴	1.2 x 10 ¹⁴	10 ¹⁶	—	—	—	10 ¹⁴	10 ¹⁴	10 ¹⁴
Arc Resistance, s	D495	129	240	136 ^a	—	—	—	—	184	182	181
Loss Factor, dimensionless	D150										
10 ² Hz		—	—	0.011	—	—	—	—	—	—	—
10 ³ Hz		—	—	0.010	—	—	—	—	—	—	—
10 ⁴ Hz		—	—	0.010	—	—	—	—	—	—	—
10 ⁶ Hz		—	—	0.024	—	—	—	—	—	—	—

^aNo sharp cutoff noted. At the value listed above, GC25 starts to melt and char.

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TABLE 3-29. PHYSICAL AND MECHANICAL PROPERTIES OF ACRYLICS¹⁸

Property	Glass Content	ASTM Test Method	THERMOCOMP	
			Non-reinforced 0%	PDX-301 20%
Specific Gravity		D792	1.17	1.33
Tensile Strength at 73 F, psi		D638	7,000-11,000	15,000
Tensile Elongation, %		D638	2.0-10.0	2-3
Flexural Strength, psi		D790	13,000-19,000	19,000
Flexural Modulus, psi		D790	460,000	950,000
Impact Strength, Izod, ft • lb/in.		D256		
notched ¼ in. bar			0.3-0.5 ^a	1.3
unnotched ¼ in. bar			—	3-4

^a¼ in. bar

Property	Glass Content	ASTM Test Method	THERMOCOMP	
			Non-reinforced 0%	PDX-301 20%
Heat Distortion Temperature, 264 psi, °F		D648	165-210	215
Flammability		D635	0.9-1.2	SB

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TABLE 3-31. PHYSICAL AND MECHANICAL PROPERTIES OF ABS

Property	ASTM Test Method	Non-reinforced	THERMOCOMP			ABSAFIL					THERMOFIL				FIBERITE RTP		
			AF-1004 20%	AF-1006 30%	AF-1008 40%	G1200/20 20%	G1200/40 40%	J1200/10 10%	J1200/20 20%	J1200/30 30%	D1300 13%	D2000 20%	D3000 30%	DSE2000 20%	603 20%	605 30%	607 40%
Specific Gravity	0792	1.06	1.20	1.28	1.38	1.23	1.36	1.14	1.23	1.29	1.14	1.23	1.29	1.43	1.18	1.28	1.38
Specific Volume, in. ³ /lb	D792	—	23.1	21.6	20.1	—	—	—	—	—	—	—	—	—	—	—	—
Water Absorption, % 24 h to saturation	D570	0.45	0.15 0.70	0.14 0.60	0.10 0.50	0.21 0.7	0.18 0.6	0.3 0.7	0.3 0.7	0.3 0.6	—	—	—	—	0.18	0.16	0.12
Mold Shrinkage, in./in. 1/8 in. ave. section 1/4 in. ave. section	D955	—	0.0015 0.0020	0.0010 0.0015	0.0010 0.0015	0.001 0.002	0.001 0.001	0.003 0.004	0.002 0.003	0.002 0.003	—	—	—	—	0.001 0.002	0.0015	0.001 0.001
Tensile Strength, psi 73° F 140° F	D638	7,500	13,500 8,500	14,500 9,000	16,000 10,500	13,000 8,000 ^a	16,000 9,000 ^a	10,000 —	12,000 —	13,000 —	10,500 —	13,000 —	14,000 —	8,500 —	13,000 —	16,000 —	18,000 —
Tensile Elongation, %	0638	5–25	3–4	3–4	2–3	2.0	1.8	2.0	1.5	1.3	4.0	3.0	2.0	2.5	2.0	1.8	1.5
Flexural Strength, psi	D790	13,000	17,500	18,500	20,000	20,000	25,000	14,000	17,000	17,000	—	—	—	—	17,000	19,000	21,000
Flexural Modulus, psi 73° F 140° F	D790	460,000	850,000 800,000	1,100,000 1,000,000	1,400,000 1,300,000	800,000 750,000 ^a	1,100,000 1,000,500 ^a	600,000 —	850,000 —	1,000,000 —	600,000 —	780,000 —	850,000 —	750,000 —	800,000 —	1,000,000 —	1,300,000 —
Compressive Strength, psi	D695	13,000	13,500	14,500	16,000	14,000	17,000	12,000	14,000	15,000	—	—	—	—	13,000	15,000	19,000
Shear Strength, psi	0732	—	7,000	7,500	8,000	8,000	9,000	6,000	7,000	8,000	—	—	—	—	—	—	—
Impact Strength, Izod, ft•lb/in. notched 1/4 in. bar unnotched 1/4 in. bar	D256	2–6 ^b	1.5 6–7	1.4 6–7	1.3 5–6	2.0 —	2.4 —	0.9 —	1.0 —	1.0 —	1.4 ^c —	1.2 ^c —	1.2 ^c —	1.6 ^c —	1.4 6.0	1.3 5.0	1.2 5.0
Rockwell Hardness	D785	R115	R124, M97	R124, M99	R124, M102	M75–85	M90–100	M55–65	M70–80	M75–85	—	—	—	—	107	110	110

^aat 170° F

^b1/2 in. bar

^c1/8 in. bar

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TABLE 3-32. PROPERTY DATA OF PLATED ABS

Property	Glass Content	ASTM Test Method	Non-reinforced	Reinforced 25%
Tensile Strength, psi		D638	7,000	7,200
Flexural Modulus, psi		D790	900,000	2,000,000
Notched Izod Impact, ft•lb/in.		0256	—	0.7
Heat Distortion Temperature at 66 psi, °F		D648	215	290

TABLE 3-33. THERMAL PROPERTIES OF ABS

Property	Glass Content	ASTM Test Method	Non-reinforced	THERMOCOMP			ABSAF IL					FIBERITE RTP		
				AF-1004 20%	AF-1006 30%	AF-1008 40%	G1200/20 20%	G1200/40 40%	J1200/10 10%	J1200/20 20%	J1200/30 30%	603 20%	605 30%	607 40%
Heat Distortion Temperature, °F at 66 psi at 264 psi		0648	210 199	225	230	235	230	240	205	215	215	220	230	240
				215	220	225	240	250	215	225	225	230'	240	245
Coefficient of Linear Thermal Expansion, (in./in. • °F) x 10 ⁻⁵		0696	8.0	2.0	1.6	1.2	2.0	1.6	—	—	—	2.0	1.7	1.3
Flammability		UL Subj. 94	—	94HB	94HB	94HB	—	—	—	—	—	SB	SB	SB
Flammability		D635	—	—	—	—	—	—	—	—	—	B	B	B
Thermal Conductivity, Btu/h•ft ² •°F/in.		C-177	1.2	—	—	—	—	—	—	—	—	1.4	1.5	1.6

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TABLE 3-34. ELECTRICAL PROPERTIES OF ABS

Property	ASTM Test Method	Glass Content Non-reinforced	ABS AFIL					THERMOFIL				FIBERITE RTP		
			G 1200/20 20%	G 1200/40 40%	J 1200/10 10%	J 1200/20 20%	J 1200/30 30%	D 1300 13%	D 2000 20%	D 3000 30%	DSE 2000 20%	603 20%	605 30%	607 40%
Dielectric Strength, V/mil short time step by step	D 149	350-500	480	-	-	-	-	480	500	510	450	400	400	400
		-	450	-	-	-	-	-	-	-	-	-	-	-
Volume Resistivity, ohm • cm	D 257	10 ¹⁶	10 ¹⁵	10 ¹⁵	10 ¹⁵	10 ¹⁶	10 ¹⁶	-	-	-	-	10 ¹⁵	10 ¹⁵	10 ¹⁵
Surface Resistivity, ohm	D 257	-	10 ¹⁶	10 ¹⁶	10 ¹⁶	10 ¹⁷	10 ¹⁷	-	-	-	-	-	-	-
Dielectric Constant, dimensionless	D 150	60 Hz	2.4-5	3.2	-	-	-	-	-	-	-	-	-	-
		10 ³ Hz	2.4-4.5	3.2	-	-	-	-	-	-	-	-	-	-
		10 ⁶ Hz	2.4-3.8	3.2	-	-	-	-	-	-	-	-	3.4	3.5
Dissipation Factor, dimensionless	D 150	60 Hz	0.003-0.008	0.006	-	-	-	-	-	-	-	-	-	-
		10 ³ Hz	0.004-0.007	0.007	-	-	-	-	-	-	-	-	-	-
		10 ⁶ Hz	0.007-0.015	0.007	-	-	-	-	-	-	-	-	0.009	0.009
Arc Resistance, tungsten electrodes, s	D 495	50-85	65	-	-	-	-	-	-	-	-	75	75	75

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TABLE 3-35. PHYSICAL AND MECHANICAL PROPERTIES OF ETFE, CTFE, AND PTFE

Property	ASTM Test Method	ETFE THERMOCOMP				CTFE		PTFE FLUON		
		Tefzel Non-reinforced	UF-1002 10%	UF-1004 20%	UF-1006 30%	PLASKON 2100 Non-reinforced	LNP 803 15%	G307 Non-reinforced	VG15F 15%	VG25F 25%
Specific Gravity	D792	1.70	1.75	1.82	1.89	2.13	2.19	2.18	2.20	2.26
Water Absorption, 24 h, %	D570	<0.02	<0.02	<0.02	<0.02	—	—	—	—	—
Mold Shrinkage, 1/8 in., in./in.	D955	0.015–0.020	0.005–0.006	0.003–0.004	0.002–0.003	—	—	—	—	—
Tensile Strength, psi	D638	6,500	8,500	11,000	14,000	4,000 ^a	5,000	4,000–5,000	3,000–5,000	2,000–5,000
Tensile Elongation, %	0638	> 100	10	7	5	140	6–8	350	300	300
Flexural Strength, psi	0790	10,000	12,500	15,000	19,000	—	—	—	—	—
Flexural Modulus, psi	0790	200,000	500,000	750,000	1,050,000	860,000	—	—	—	—
Izod Impact Strength, ft•lb/in. notched 1/4 in. unnotched 1/4 in.	D256	NB	6	7	7.5	1.2 ^a	1.2 ^a	4.3 ^a	2.3 ^a	2.3 ^a
		NB	8–10	12–14	17–18	—	—	—	—	—
Shear Strength, psi	0732	6,000	6,000	6,500	7,000	—	—	—	—	—
Compressive Strength, psi	0695	7,000	8,000	9,500	1,150	—	—	—	—	—
Wear Factor K, Equilibrium $\left(\frac{\text{in.}^3 \cdot \text{min}}{\text{ft} \cdot \text{lb} \cdot \text{h}}\right) \times 10^{-10}$	LNP	6,000	28	25	26	—	—	—	—	—
Coefficient of Friction, dimensionless static at 40 psi dynamic at 40 psi, 50 fpm	LNP	0.50	0.46	0.42	0.40	—	—	—	—	—
		0.40	0.33	0.29	0.26	—	—	—	—	—

^a 1/8 in. bar

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TABLE 3-36. THERMAL PROPERTIES OF ETFE AND CTFE

Glass Content Property	ASTM Test Method	ETFE THERMOCOMP				CTFE	
		Tefzel	UF-1002	UF-1004	UF-1006	PLASKON	LNP
		Nonreinforced	10%	20%	30%	2100 Nonreinforced	803 15%
Heat Distortion at 264 psi, -F	D648	160	390	440	460	258 ^a	200
Coefficient of Linear (Thermal Expansion) (in./in. • °F) x 10 ⁻⁵	0696	4.2	2.8	2.0	1.6	—	—
UL Flammability	Subj. 94	SE 0	SE 0	SE 0	SE 0	Nonflam.	Nonflam.

^a66 psi

TABLE 3-37. ELECTRICAL PROPERTIES OF ETFE

Glass Content Property	ASTM Test Method	ETFE	
		Nonreinforced	Glass Reinforced
Dielectric Strength, short time, 1/8 in. thickness, V/mil	0149	400	425
Dielectric Constant, dimensionless	0150		
60 Hz		2.6	3.4
10 ³ Hz		2.6	3.4
10 ⁶ Hz		2.6	3.4
Dissipation (power) Factor, dimensionless	0150		
60 Hz		—	0.004
10 ³ Hz		0.0008	0.002
10 ⁶ Hz		0.005	0.005
Volume Resistivity, ohm • cm	D257	> 10 ¹⁶	10 ¹⁶
Arc Resistance, s	0495	72	110

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TABLE 338. PHYSICAL AND MECHANICAL PROPERTIES OF NYLON 6^a

Property	ASTM Test Method	NYLON 6 THERMOCOMP							NYLON 6		NYPEL				PLASKON			NYLAFIL					THERMOFIL			FIBERITE RTP				
		Non-reinforced	PF-1002 10%	PF-1004 20%	PF-1006 30%	PF-1008 40%	PF-100-10 50%	PF-100-12 60%	PFL-4216 w/30% & 5% MoS ₂ ^b	PFL-4218 w/40% & 5% MoS ₂ ^b	6010 10%	6014 14%	6020 20%	6030 30%	6030MS 30% plus MoS ₂ ^b	8230 6%	8231 14%	8233 30%	G3/30 30%	G 1/30/MS/5 30% & 5% MoS ₂ ^b	J3/30 30%	5-13/40 40%	S-3/30 30%	N6000	N1300	N3000	203A 20%	205A 30%	207A 40%	
Specific Gravity	D792	1.13-1.15	1.21	1.28	1.37	1.46	1.57	1.70	1.43	1.56	1.20	1.22	1.28	1.37	1.42	1.17	1.22	1.37	1.40	1.49	1.40	1.49	1.40	1.17	1.20	1.37	1.27	1.36	1.46	
Specific Volume, in. ³ /lb		—	22.9	21.7	20.2	19.0	17.6	16.3	19.4	17.7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
Water Absorption, % 24 h equil. cont. immersion	D570	1.8 9.5	1.4 8.8	1.3 8.0	1.1 6.5	0.9 4.6	0.8 4.3	0.7 4.0	1.0 6.0	0.8 3.9	1.6 —	1.55 —	1.45 —	1.3 —	—	—	—	—	1.3 6.4	1.1 4.0	1.3 6.4	1.1 4.0	1.3 6.4	—	—	—	1.3 —	1.2 —	1.0 —	
Mold Shrinkage, in./in. 1/8 in. ave. section 1/4 in. ave. section	D955	0.013 0.016	0.0060 0.0100	0.0045 0.0065	0.0035 0.0045	0.0030 0.0040	0.0025 0.0035	0.0020 0.0030	0.004 0.005	0.004 0.005	—	—	—	—	—	—	—	0.003 0.004	0.002 0.003	0.003 0.004	0.002 0.003	0.003 0.004	—	—	—	0.004 0.007	0.003 0.005	0.002 0.003		
Tensile Strength, psi	D638	11,800	13,500	18,500	23,000	26,000	31,000	33,000	18,500	25,000	13,200	14,600	16,200	19,500	18,500	13,000	12,300	15,000	26,000	39,000	26,000	39,000	23,000	12,500	16,000	23,000	20,000	23,000	25,000	
Tensile Elongation, %	D638	80	3-4	3-4	3-4	2-3	2-3	1-2	3-4	3	—	—	—	—	—	—	3.5	3.5	2.0	2.1	2.2	2.8	3.0	4.0	3.5	3	3.0	3.0	2.0	
Flexural Strength, psi	D790	15,000	17,000	28,500	34,000	36,000	45,000	49,000	28,000	33,000	20,000	21,000	23,000	29,000	26,300	17,000	22,500	35,000	28,000	42,000	28,000	35,000	28,000	—	—	—	23,000	28,000	31,000	
Flexural Modulus, psi	D790	400,000	650,000	850,000	1,200,000	1,500,000	2,000,000	2,800,000	1,100,000	1,500,000	630,000	700,000	800,000	1,300,000	1,350,000	500,000	750,000	1,350,000	1,000,000	1,400,000	1,000,000	1,400,000	800,000	700,000	850,000	1,000,000	700,000	1,100,000	1,300,000	
Compressive Strength, psi	D695	8,800	16,000	22,000	23,000	23,000	24,000	25,000	21,000	24,000	—	—	—	—	—	—	—	—	24,000	25,000	24,000	25,000	19,000	—	—	—	21,000	22,000	23,000	
Shear Strength, psi	D732	9,600	9,700	10,000	12,000	12,500	13,000	13,500	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Izod Impact Strength, ft•lb/in. notched 1/4 in. x 1/2 in. bar unnotched 1/4 in. x 1/2 in. bar	D256	1.0 —	1.0 5-6	1.4 11-12	2.3 20	3.0 20	4.0 20	4.0 20	1.6-2.0 12	1.6-2.0 16	1.1 —	1.0 —	1.1 —	1.6 —	1.0 —	0.8 —	0.9 —	2.1 —	3.0 —	4.0 —	2.0 —	2.5 —	1.6 —	1.8' —	1.4' —	1.5' —	1.3 9.0	2.0 12.0	2.5 16.0	
Rockwell Hardness	D785	R119 —	R118 M86	R119 M88	R121 M92	R121 M92	R121 M98	R121 M101	— M94	— M94	— M76	— M84	— M86	— M90	— —	R121 —	R121 —	R121 —	E50-60 —	E60-70 —	E50-60 —	E50-60 —	E45-55 —	— —	— —	— —	R118 —	R119 —	R120 —	

^a Test specimens dry, as molded except where otherwise specified.
^b MoS₂ = molybdenum disulfide
^c 1/8 in. bar

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TABLE 3-40. PHYSICAL AND MECHANICAL PROPERTIES OF NYLONS 6/10

Property	ASTM Test Method	THERMOCOMP							NYLAFIL					THERMOFIL		
		Non-reinforced	QF-1002 10%	QF-1004 20%	QF-1006 30%	OF-1008 40%	QF-100-10 50%	OF-100-12 60%	G2/30 30%	G 12/40 40%	5-2/30 30%	J-12/40 40%	s-2/30 30%	N5-1500 15%	N5-3300 33%	N5-5000 50%
Specific Gravity	0792	1.07–1.09	1.15	1.22	1.30	1.41	1.50	1.65	1.35	1.46	1.35	1.46	1.35	1.26	1.37	1.50
Specific Volume, in. ³ /lb	0792	–	24.1	22.7	21.3	19.8	18.2	16.8	–	–	–	–	–	–	–	–
Water Absorption, % 24 h to saturation	0570	0.40 3.50	0.24 3.20	0.22 2.00	0.20 1.85	0.18 1.80	0.16 1.40	0.14 0.85	0.2 2.1	0.2 1.9	0.2 2.1	0.2 1.9	0.2 2.1	–	–	–
Mold Shrinkage, in./in. 1/8 in. ave. section 1/4 in. ave. section	0955	0.013 0.016	0.0045 0.0060	0.0040 0.0050	0.0035 0.0045	0.0030 0.0040	0.0025 0.0035	0.0020 0.0030	0.003 0.004	0.002 0.003	0.003 0.004	0.002 0.003	0.003 0.004	–	–	–
Tensile Strength, psi	0638	8,500	12,000	18,000	21,000	26,000	29,000	31,000	23,000	30,000	23,000	29,000	18,000	13,000	21,000	28,000
Tensile Elongation, %	0638	85	3–4	3–4	3–4	2–3	2–3	1–2	1.9	2.2	2.5	3.0	2.8	4.0	3.0	1.5
Flexural Strength, psi	0790	12,000	17,000	26,000	32,000	35,000	43,000	46,000	28,000	42,000	28,000	35,000	28,000	–	–	–
Flexural Modulus, psi	0790	280,000	750,000	900,000	1,100,000	1,300,000	1,900,000	2,300,000	800,000	1,500,000	800,000	1,500,000	750,000	950,000	1,200,000	1,750,000
Shear Strength, psi	0732	8,400	8,600	9,400	11,000	12,000	12,500	13,000	11,000	12,000	11,000	12,000	8,000	–	–	–
Compressive Strength, psi	0695	3,000(1%)	14,000	17,000	20,000	23,000	25,000	26,000	24,000	25,000	24,000	25,000	18,000	–	–	–
Izod Impact Strength, ft•lb/in. notched 1/4 in. bar unnotched 1/4 in. bar	0256	0.6 –	0.9 6–7	1.1 12–13	2.4 20.0	3.2 20.0	4.5 20.0	4.5 20.0	3.4 –	4.5 –	2.2 –	2.5 –	1.6 –	1.4 ^a –	1.9 ^a –	2.4 ^a –
Rockwell Hardness	0785	R111 –	R117 M87	R119 M89	R120 M93	R121 M93	R 122 M99	R123 M102	– E40–50	– E55–65	– E50–60	– E50–60	– E30–40	–	–	–

^a 1/8 in. bar

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TABLE 3-41. PHYSICAL PROPERTIES OF MOISTURE CONDITIONED (50% RH) GLASS-REINFORCED THERMOCOMP NYLON RESINS

Glass Content Property	ASTM Test Method	Nylon 6		Nylon 6/6		Nylon 6/10	
		RF-1006 30%	RF-1008 40%	RF-1006 30%	RF-1008 40%	QF-1006 30%	OF-1008 40%
Tensile Strength, psi 73° F 170° F	D638	18,000	22,000	20,000	25,000	20,000	23,000
		12,000	15,500	13,000	16,500	13,000	16,000
Tensile Elongation, % 73° F 170° F	D638	6-7	3-4	6-7	3-4	5-6	4-5
		7-8	4-5	7-8	4-5	8-10	6-7
Flexural Strength, psi 73° F 170° F	D790	24,000	31,000	25,000	35,000	31,000	32,000
		17,000	19,000	20,000	24,000	18,000	19,000
Flexural Modulus, psi 73° F 170° F	D790	700,000	900,000	800,000	1,100,000	1,000,000	1,200,000
		500,000	750,000	500,000	750,000	500,000	750,000
Izod Impact Strength, notched bar ¼ in. x ½ in ft • lb/in. 73° F 170° F	D256	5.5	6.4	3.0	3.3	3.2	3.6
		7.2	8.4	4.0	4.2	5.3	7.5
Fatigue Endurance Limit, psi	D671	—	—	—	7,000	—	6,700

TABLE 342. LIMITING PRESSURE VELOCITY OF THERMOCOMP NYLON 6, 6/6, and 6/10¹⁴

Resin	LNP Series Code	PTFE Lubricant, wt%	Glass Content, wt%	Limiting PV		
				10 ft/min	100 ft/min	1,000 ft/min
Nylon 6	PFL 4036	15	30	17,500	20,000	13,000
Nylon 6/10	QFL 4036	15	30	20,000	15,000	12,000
Nylon 6/6	R 1000	—	—	3,000	2,500	<2,500
Nylon 6/6	RF 1006	30	—	12,500	10,000	7,500
Nylon 6/6	RL 4010	5	—	12,500	7,500	3,000
Nylon 6/6	RL 4040	20	—	14,000	27,500	8,000
Nylon 6/6	RFL 4036	15	30	17,500	20,000	17,000

TABLE 3-43. WEAR AND FRICTIONAL PROPERTIES OF THERMOCOMP NYLON 6, 6/6, and 6/10¹⁴

Resin	LNP Series Code	PTFE Lubricant, wt %	Glass Content, wt %	K-factor, ^{a,b} $\left(\frac{\text{in.}^3 \cdot \text{min}}{\text{ft} \cdot \text{lb} \cdot \text{h}}\right) \times 10^{-10}$	Coefficient of Friction ^b	
					Static (40 psi)	Dynamic (40 psi, 50 ft/min)
Nylon 6	P 1000	—	—	200	0.22	0.26
Nylon 6	PL 4030	15	—	15	0.09	0.19
Nylon 6	PFL 4036	15	30	17	0.20	0.25
Nylon 6/10	QFL 4036	15	30	15	0.23	0.31
Nylon 6/6	R 1000	—	—	200	0.20	0.26
Nylon 6/6	RL 4010	5	—	60	0.13	0.20
Nylon 6/6	RL 4040	20	—	12	0.10	0.18
Nylon 6/6	RFL 4036	15	30	16	0.19	0.26
Nylon 6/6	RF 1002	—	10	80	0.17	0.16
Nylon 6/6	RF 1006	—	30	75	0.21	0.20
Nylon 6/6	RF 1008	—	40	70	0.22	0.21
Nylon 6/6	RF 100-12	—	60	44	0.23	0.21
Nylon 6/10CB ^c	QFL 4036CB	15	30	8	0.18	0.17

^aK-factor values to be multiplied by 10¹⁰^bMated against SAE 1040 steel^cSilicone Constant Bleed Compounds

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TABLE 3-44. PHYSICAL AND MECHANICAL PROPERTIES OF NYLON 6/12

Property	Glass Content	ASTM Test Method	ZYTEL 158 Nonreinforced	THERMOCOMP			NYLAFIL				ZYTEL	
				IF-1005 25%	IF-1007 35%	IF-1009 45%	G-4/35 35%	G-4/45 45%	J-4/35 35%	5-4/45 45%	77G-33 33%	77G-43 43%
Specific Gravity		D792	1.07	1.26	1.35	1.46	—	—	—	—	1.32	1.46
Water Absorption, %		0570										
24 h			0.4	0.22	0.20	0.15	0.2	0.2	0.2	0.2	0.2	0.2
to saturation			—	—	—	—	2.1	1.9	2.1	1.9	2.0	1.7
Mold Shrinkage, mil/in.												
5 in. x 1/2 in. x 1/8 in. bar (flow dir)			—	—	—	—	—	—	—	—	3.0	2.0
2 in. x 1/8 in. disc (transverse dir)			—	—	—	—	—	—	—	—	9.0	8.0
Tensile Strength, Yield, psi		0638	8,800	20,000	24,000	30,000	24,000	30,000	22,000	26,000	24,000	28,000
Elongation, Yield, %		D638	340 ^b	5-6	4-5	4-5	3.2	2.9	5.0	4.5	4.5	4.0
Flexural Strength, psi		D790	—	28,000	34,000	39,000	36,000	42,000	33,000	39,000	37,000	43,000
Flexural Modulus, psi		D790	180,000	1,000,000	1,300,000	1,600,000	1,100,000	1,550,000	1,100,000	1,450,000	1,200,000	1,500,000
Compressive Strength, psi		D695	—	27,000	23,000	24,000	19,500	22,000	21,000	23,000	23,000	23,500
Shear Strength, psi		D732	—	10,000	11,000	12,000	10,000	11,000	9,500	10,000	11,000	12,000
Izod Impact Strength, ft•lb/in.		D256										
notched 1/4 in. bar			1.4	2.0	3.0	3.6	4.2	5.7	3.0	3.4	2.6 ^a	3.3 ^a
unnotched 1/4 in. bar			—	13	15	15	—	—	—	—	25.0 ^a	28.0 ^a
Rockwell Hardness		0785	R114	R119	R120	R121	—	—	—	—	—	—

^a 1/8 in. bar^b at break

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TABLE 3-45. PHYSICAL AND MECHANICAL PROPERTIES OF RILSAN NYLON 11^a (REF. 19)

Property \ Glass Content	ASTM Test Method	RILSAN					
		BMN Non-reinforced	ZM 30 30%	ZM 23 G9 23%	ZM 43 G9 43%	ZM 30 BLACK W3 30%	ZM 30 BLACK TL 30%
Viscosity, Viscosity Index at 25° C, average value	ISO R-307	128	150	150	150	135	150
Specific Gravity	D792	1.04	1.26	1.22	1.42	1.27	1.26
Melting Point, °C	D789	185	185	185	185	185	185
Water Absorption at Equilibrium, %	D570						
20° C and 65% RH		1.1	0.54	0.50	0.49	0.54	0.54
20° C and 100% RH		1.9	1.30	1.1	1.0	1.30	1.30
100° C and 100% RH		2.9	1.6	1.6	1.5	1.6	1.6
Water Absorption, 24 h, %	D570	0.23	0.12	0.10	0.10	0.12	0.12
Tensile Strength at Break, kgf/mm ²	D638						
-40° C		7.0	10.0	10.0	14.0	10.0	0.0
+20° C and 65% RH		5.5	9.5	9.6	13.6	9.6	9.3
+20° C and 100% RH		6.0	3.5	4.0	4.0	3.5	3.4
+80° C		4.3	5.1	5.0	5.5	5.1	5.0
Elongation at Break, %	D638						
-40° C		37	4	4	4	4	4
+20° C and 65% RH		329	5	6	4	4	6
+20° C and 100% RH		320	6	6	5	5	7
+80° C		405	12	7	6	10	12
Elastic Modulus in Flexure, kgf/mm ²	D790						
-40° C		135	950	1000	1500	960	900
+20° C and 65% RH		100	320	290	410	300	250
+20° C and 100% RH		97	215	193	270	200	170
+80° C		19	107	95	140	100	85

^a For all measurements made on unsaturated test pieces, the moisture content can vary between grades from 0.30–0.40%.

TABLE 3-46. PHYSICAL AND MECHANICAL PROPERTIES OF THERMOCOMP NYLON 11²⁰

Property	Glass Content	ASTM Test Method	THERMOCOMP	
			Nonreinforced	HF-1006
Specific Gravity		D792	1.05	1.24
Tensile Strength at Yield, psi		D638	7,800	14,000
Ultimate Elongation, %		D638	300	3-4
Flexural Strength, psi		D790	7,800	20,000
Flexural Modulus, psi		D790	142,000	875,000
Izod Impact, ¼ in. bar, ft•lb/in.		D256	1.8	2.2
			—	7-8

TABLE 4-47 ON NEXT PAGE.

TABLE 3-48. PHYSICAL AND MECHANICAL PROPERTIES OF NYLON 12

Property	Glass Content	ASTM Test Method	LNP	THERMOFIL	
			SF-1006 30%	N9-3000 30%	N9-5000 50%
Specific Gravity		D792	1.23	1.35	1.46
Mold Shrinkage, mils/in.		D955	—	6	3
Tensile Stress at Yield, psi		D638	17,400	14,500	17,000
Tensile Elongation, %		D638	3-4	4	2.5
Flexural Modulus, psi x 10 ⁵		D790	10.0	9.0	14.0

TABLE 3-47. PHYSICAL AND MECHANICAL PROPERTIES OF VESTAMID NYLON 12**

Property \ Glass Content	Measured by ISO ^a	Test Method Equivalent ASTM	Methods BS	VESTAMID	
				L 1801 Non-reinforced	L 1930 L1931 30%
Density (bulk factor), g/cm ³	ISO R 1183 (Method A)	ASTM D792 (Method A)	BS 2782 Part 5/509 A	1.01–1.02	1.21–1.26
Apparent Bulk Density, g/cm ³	ISO R 60	ASTM 1895 (Method A)	BS 2782 Part 5/501 A	0.5–0.6	0.6–0.7
Maximum Water Absorption, %	after immersion in water at 23° C at 65% RH, 20" C			1.5 0.9	1.0 0.6
Water Absorption (test specimen 50 mm × 50 mm × 1 mm), mg	ISO R 62 (Method A)		Part 5/502F	14	10
Tensile Stress at Yield, N/mm ²				50	65
Elongation at Yield, %	ISO R 527 Speed D	ASTM D638		6	5
Tensile Stress at Break, N/mm ²	Test spec. acc. to Fig. 1	Speed D Test spec. Type 1		55	65
Elongation at Break, %				200	5
Compressive Strength, N/mm ²	ISO DIS 2038			50	60
Modulus of Elasticity in Flexure, kN/mm ²	ISO R 178		BS 2782 Part 3/304 E	1.5	–
Flexural Stress at Conventional Deflection, N/mm ²	ISO R 178		BS 2782 Part 3/304 E	50	90
Ball indentation Hardness 30 (Load 358 N = 36.5 kgf), N/mm ²	ISO DIS 2039			98	120
Shore Hardness, D	ISO R 869			75	78
Rockwell Hardness, R		ASTM D785		110	113
Impact Resistance (Charpy Impact Flexural Test), kJ/m ²	ISO R 179 Test spec acc to Fig. 2			no break	50
Impact Resistance (notched) +20° C (Charpy), kJ/m ²				12	8
Impact Resistance (Impact) -40° C (Flexural Test), kJ/m				8	5
Impact Resistance (notched) (Izod Impact Flexural Test), J/m	ISO R 180 Method A	ASTM D256 Method A		60	70

^a ISO = International Organization for Standardization

Conversion table: 1 kgf/cm² ≈ 0.1 N/mm²

1 cm • kgf/cm² ≈ 1 kJ/m²

1 cm • kgf/cm of notch ≈ 10 J/m

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TABLE 3-49. THERMAL PROPERTIES OF NYLON 6

Glass Content	ASTM Test Method	Non-reinforced	THERMOCOMP PF SERIES								NYPEL				
			PF 1002 10%	PF 1004 20%	PF 1006 30%	PF 1008 40%	PF 100-10 50%	PF 100-12 60%	PFL-4216 30%, 5% MoS ₂	PFL-4218 40%, 5% MoS ₂	6010 10%	6014 14%	6020 20%	6030 30%	6030 MS 30%, MoS ₂
Deformation Under Load, % 2000 psi, 122° F 4000 psi, 122° F, 24 h	D621	1.6	— 1.4	— 1.0	— 0.9	— 0.4	— 0.3	— 0.2	<0.1 0.5	<0.1 0.4	— 0.6	— —	— —	— 0.1	— —
Deflection Temperature, °F 66 psi 264 psi	D648	347 167	410 375	420 410	425 420	425 420	425 420	425 420	425 420	430 422	413 346	419 376	424 394	428 418	428 420
Thermal Conductivity, Btu/h•ft ² •°F/in.	Cenco	1.3	2.5	2.7	3.3	3.4	3.5	3.6	—	—	—	—	—	—	—
Coefficient of Linear Thermal Expansion, (in./in.°F) × 10 ⁻⁵	D696	4.6	2.5	2.2	1.7	1.2	0.9	0.8	1.9	1.0	—	—	—	—	—
Flammability	UL Subj. 9 ⁴ D635	— SE	— —	— —	— —	— —	— —	— —	94HB —	94HB —	— —	— —	— —	— —	— —

Glass Content	ASTM Test Method	Non-reinforced	PLASKON			NYLAFIL					THERMOFIL			FIBERITE RTP		
			8230 6%	8231 14%	8233 30%	6-3/30 30%	G-13/40 40%	J-3/30 30%	5-13/40 40%	S-3/30 30%	N 0500 5%	N 1500 15%	N 3000 30%	203A 20%	205A 30%	207A 40%
Deformation Under Load, % 2000 psi, 122° F 4000 psi, 122° F, 24 h	D621	1.6	— —	— —	— —	— 0.6	— 0.4	— 0.6	— 0.4	— 0.6	— —	— —	— —	— —	— —	— —
Deflection Temperature, °F 66 psi 264 psi	D648	347 167	400 300	420 390	420 420	425 420	430 425	420 405	425 405	420 400	— 300	— 370	— 415	410 390	420 400	420 400
Thermal Conductivity, Btu/h•ft ² •°F/in.	Cenco	1.3	—	—	—	1.7	—	—	—	—	—	—	—	3.0	3.5	3.6
Coefficient of Linear Thermal Expansion, (in./in.°F) × 10 ⁻⁵	D696	4.6	3.3	2.8	2.1	1.6	1.1	1.6	1.5	1.8	—	—	—	2.3	1.75	1.3
Flammability	UL Subj. 9 ⁴ D635	— SE	SB —	SB —	SB —	— —	— —	— —	— —	— —	— —	— —	— —	SB B	SB B	SB B

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TABLE 3-50. THERMAL PROPERTIES OF NYLON 6/6

Property \ Glass Content	ASTM Test Method	Non-reinforced	NYLAFIL												
			6-1/30 30%	G-1/30/EM 30%	G-10/40 40%	6-1/30 /MS/5 30%, 5% MoS ₂	G-10/40 /MS/5 40%, 5% MoS ₂	6-1/30 /TF/22 30%, 22% TFE	5-1/30 30%	J-1/30/EM 30%	J-10/40 40%	5-1/30 /MS/5 30%, 5% MoS ₂	5-1/30 /TF/22 30% FG 22% TFE	S-1/30 30%	S-1/30 /MS/5 30%, 5% MoS ₂
Deformation Under Load, % 2000 psi, 122" F, 24 h 4000 psi, 122" F	D621	1.4 —	— 0.4	— 0.6	0.4 0.4	— 0.4	— 0.4	— 0.5	— 0.4	— 0.6	0.4 0.4	— 0.4	— 0.5	— 0.4	— 0.4
Deflection Temperature, °F 66 psi 264 psi	D648	360 150	505 495	475 460	510 500	505 495	510 500	500 490	500 485	465 450	500 485	490 480	490 460	500 480	500 480
Thermal Conductivity, Btu/h•ft ² •°F/in.	Cenco	1.7	1.5	—	3.3	—	—	—	—	—	—	—	—	—	—
Coefficient of Linear Thermal Expansion, (in./in.•°F) x 10 ⁻⁵	D696	4.5	2.1	1.8	1.4	1.6	1.4	2.1	2.1	1.8	1.6	1.6	2.1	2.1	1.9
Flammability	UL Subj. 94 D635	— SE	— —	— —	— —	— —	— —	— —	— —	— —	— —	— —	— —	— —	— —

Property \ Glass Content	ASTM Test Method	Non-reinforced	THERMOCOMP								ZYTEL						
			RF 1002 10%	RF 1004 20%	RF 1006 30%	RF 1008 40%	RF 100-10 50%	RF 100-12 60%	RFL-4216 30%, 5% MoS ₂	RFL-4218 40%, 5% MoS ₂	706-13 13%	706-23 23%	70G-33 33%	70G-43 43%	716-13 13%	716-33 33%	
Deformation Under Load, % 2000 psi, 122" F, 24 h 4000 psi, 122" F	D621	1.4 —	— 0.9	— 0.7	— 0.6	— 0.4	— 0.3	— 0.2	— 0.2	<0.1 0.4	<0.1 0.3	— 1.1	— 1.0	— 0.8	— 0.7	— 1.7	— 1.3
Deflection Temperature, °F 66 psi 264 psi	D648	360 150	500 485	500 485	500 490	500 500	500 500	500 500	500 500	485 475	490 485	— 470	— 480	— 480	— 485	— 450	— 475
Thermal Conductivity, Btu/h•ft ² •°F/in.	Cenco	1.7	2.7	2.9	3.4	3.6	3.8	4.0	—	—	—	—	—	—	—	—	—
Coefficient of Linear Thermal Expansion, (in./in.•°F) x 10 ⁻⁵	D696	4.5	2.7	2.3	1.8	1.4	1.0	0.9	—	2.0	1.3	1.5	1.4	1.3	1.2	1.3	1.0
Flammability	UL Subj. 94 D635	— SE	— —	— —	— —	— —	— —	— —	— —	94HB —	94HB —	— —	— —	— —	— —	— —	— —

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TABLE 3-50. (cont'd)

Property	ASTM Test Method	Non-reinforced	NYPEL					THERMOFIL					FIBERITE RTP			
			6610 10%	6614 14%	6620 20%	6630 30%	6630 MS 30% + MoS ₂	N3-1500 15%	N3-3010 30% + MoS ₂	N3-3020 30% + TFE	N3-3300 33%	N3-4300 43%	N3SE 3000 30%	203 20%	205 30%	207 40%
Deformation Under Load, % 2000 psi, 122° F, 24 h 4000 psi, 122° F	D621	1.4	—	—	—	—	—	—	—	—	—	—	—	—	—	—
		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Deflection Temperature, °F 66 psi 264 psi	D648	360	488	494	497	500	500	—	—	—	—	—	—	480	500	500
		150	426	444	454	466	470	450	475	475	480	495	460	470	480	480
Thermal Conductivity, Btu/h•ft ² •°F/in.	Cenco	1.7	—	—	—	—	—	—	—	—	—	—	—	3.0	3.5	3.6
Coefficient of Linear Thermal Expansion, (in./in.•°F) x 10 ⁻⁵	D696	4.5	—	—	—	—	—	—	—	—	—	—	—	2.4	2.0	1.9
Flammability	JL Subj. 94 D635	—	—	—	—	—	—	—	—	—	—	—	—	HB	HB	HB
		SE	—	—	—	—	—	—	—	—	—	—	—	B	B	B

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TABLE 3-51. THERMAL PROPERTIES OF NYLON 6/10

Property	Glass Content	ASTM Test Method	Non-reinforced	THERMOCOMP						NYLAFIL					THERMOFIL		
				QF-1002 10%	QF-1004 20%	QF-1006 30%	QF-1008 40%	RF-100-10 50%	RF-100-12 60%	6-2/30 30%	6-12/40 40%	5-2/30 30%	5-12/40 40%	S-2/30 30%	N5-1500 15%	N5-3300 33%	N5-5000 50%
Deformation Under Load, % 2000 psi, 122" F, 24 h 4000 psi, 122" F	D621	4.2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
			—	2.0	1.4	0.9	0.5	0.3	0.2	0.5	0.4	0.5	0.4	0.4	—	—	—
Deflection Temperature, "F 66 psi 264 psi	D648	300	410	420	430	435	435	435	435	440	420	425	420	—	—	—	
		135	400	410	420	420	425	425	420	425	400	400	400	405	420	425	
Thermal Conductivity, Btu/h•ft ² •°F/in.	Cenco	1.5	2.0	3.0	3.5	3.7	4.0	4.2	1.6	3.2	—	—	—	—	—	—	
Coefficient of Linear Thermal Expansion, (in./in.•°F) x 10 ⁻⁵	D696	5.0	2.5	2.2	1.5	1.2	0.9	0.8	1.7	1.4	1.7	1.5	1.9	—	—	—	
Flammability	JL Subj. 9 ^a	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	

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TABLE 3-52. THERMAL PROPERTIES OF NYLON 6/12

Property \ Glass Content	ASTM Test Method	ZYTEL		THERMOCOMP		
		77G-33 33%	776-43 43%	IF-1005 25%	IF-1007 35%	IF-1009 45%
Melting Point, °F	D789	415	415	—	—	—
Deflection Temperature 264 psi, °F	D648	410	410	410	415	420
Deformation Under Load 4000 psi, 122° F, %	D621	1.0	0.5	—	—	—
Coefficient of Linear Expansion, (in./in. • °F) × 10 ⁻⁵	D696	1.3	1.2	—	—	—

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Property	Glass Content	ASTM Test Method	RILSAN					THERMOCOMP	
			BMN Nonreinforced	ZM30 30% GF	ZM23G9 23% GF	ZMG9 43%	ZM30 Black W3 30%	ZM30 Black TL 30%	HF 1006
Heat Distortion Temperature, °C load 4.6 bars (66 psi) load 18.5 bars (264 psi)		D648	150	180	185	188	184	180	—
			55	173	176	183	172	173	170
Compressive Strength at 25° C, kgf/mm ²		D695	5.5	9.0	9.6	13.0	9.0	5.5	—
Linear Coefficient of Thermal Expansion (average values) ^b , (in./in.·°F) x 10 ⁻⁵		D696	<40° C:9.1; from +40° to +120° C:15	from -30° to +100° C:3	from -30° to +100° C:3	between +50° and +150° C:1.3	between +20° and +150° C:2	from -30° to +100° C:3	—
Flame Resistance		D635	self-extinguishing	burns at 27 mm/min	burns at 27 mm/min	burns at 27 mm/min	self-extinguishing ^a	burns at 27 mm/min	—

^a Dry as molded

^b This is an average value. Taking into account the anisotropic nature of the material, the linear coefficient of thermal expansion varies as a function of the orientation of the glass fibers.

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TABLE 3-54. THERMAL PROPERTIES OF VESTAMID NYLON 12²¹

Property	Measured by ISO ^a	Test Method Equivalent ASTM	Methods BS	VESTAMID	
				L 1801 Non-reinforced	L 1930 L 1931
Melting Range, °C				172–180	175–180
Vicat Softening Temperature, °C	ISO R 306		BS 2782	170	176
	9.81 N (1kgf) 49.05 N (5kgf)		Part 1/102 D	140	160
Deflection Temperature Under Load, °C	ISO R 75	D648	2782 Part 1	55	120
	Method A Method B		102 G 2782 Part 1	150	165
Median Coefficient of Linear Thermal Expansion (-40° C up to room temperature), K ⁻¹ x 10 ⁻⁵			102 H	11	3–7 ^b
Thermal Conductivity ^c , W/K•m				0.3	0.25
Long-Term Thermal Stress (> 10 ⁴ h), °C	in air			80	110
	in water			80	80
	in oil			130	140
Short-Term Thermal Stress, °C				150	165

^a ISO = International Organization for Standardization

^b The lower value is measured parallel to orientation of glass fibers, the upper value perpendicular to it.

^c Conversion table $\frac{1 \text{ kcal}}{\text{h} \cdot \text{°C} \cdot \text{m}} = 1.16 \text{ W/K} \cdot \text{m}$

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TABLE 3-55. ELECTRICAL PROPERTIES OF NYLON 6

Property	ASTM Test Method	Non-reinforced	THERMOCOMP		NYLAFIL					NYPEL	
			PF-1006 30%	PF-1008 40%	G-3/30 30%	G-13/40 40%	J-3/30 30%	J-13/40 40%	S-3/30 30%	6014 14%	6030 30%
Dielectric Strength, V/mil	D 149	420	450	420	400	580	400	580	450	445	485
Volume Resistivity, ohm. cm	D257	3.6×10^{13}	2.8×10^{14}	7×10^{13}	10^{15}	10^{14}	10^{15}	10^{14}	10^{17}	1.1×10^{15}	2.5×10^{15}
Surface Resistivity, ohm	D257	—	9×10^{13}	2×10^{13}	10^{16}	10^{15}	10^{16}	10^{15}	10^{18}	—	—
Arc Resistance, s	D495	—	135	135	90	90	90	90	120	—	—
Dielectric Constant, dimensionless	D 150										
10 ² Hz		3.8	4.2	4.4	4.6	4.4	4.6	4.5	4.4	4.12	4.07
10 ³ Hz		3.7	3.9	4.0	4.4	4.2	4.4	4.3	4.3	3.90	3.94
10 ⁶ Hz		3.4	3.6	3.9	3.9	4.0	3.9	4.1	3.9	3.54	3.72
Dissipation Factor, dimensionless	D 150										
10 ² Hz		0.010	0.009	0.010	0.024	0.020	—	—	0.001	0.020	0.0073
10 ³ Hz		0.016	0.014	0.016	0.022	0.016	—	—	0.016	0.020	0.010
10 ⁶ Hz		0.025	0.018	0.021	0.019	0.021	—	—	0.018	0.018	0.014

Property	ASTM Test Method	Non-reinforced	PLASKON			THERMOFIL			FIBERITE RTP		
			8230 6%	8231 14%	8233 30%	N-0500 5%	N-1500 15%	N-3000 30%	203A 20%	205A 30%	207A 40%
Dielectric Strength, V/mil	D149	420	420	470	510	450	480	520	500	500	500
Volume Resistivity, ohm • cm	D257	3.6×10^{13}	—	—	—	—	—	—	10^{14}	10^{14}	10^{14}
Surface Resistivity, ohm	D257	—	—	—	—	—	—	—	—	—	—
Arc Resistance, s	0495	—	—	—	—	—	—	—	110	120	120
Dielectric Constant, dimensionless	D 150										
10 ² Hz		3.8	3.9	3.9	4.4	—	—	—	—	—	—
10 ³ Hz		3.7	3.8	3.8	4.3	—	—	—	—	—	—
10 ⁶ Hz		3.4	3.3	3.5	3.8	—	—	—	3.7	3.8	4.0
Dissipation Factor, dimensionless	0150										
10 ² Hz		0.010	0.017	0.019	0.032	—	—	—	—	—	—
10 ³ Hz		0.016	0.019	0.022	0.032	—	—	—	—	—	—
10 ⁶ Hz		0.025	—	0.020	0.022	—	—	—	0.018	0.017	0.015

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TABLE 3-56. ELECTRICAL PROPERTIES OF NYLON 6/6

Glass Content Property	ASTM Test Method	Non-reinforced	THERMOCOMP		ZYTEL		THERMOFIL			FIBERITE RTP		
			RF-1006 30%	RF-1008 40%	70G-33 NC10 33%	716-33 NC10 33%	N3-3300 33%	N3-4300 43%	N3SE- 3000 30%	203 20%	205 30%	207 40%
Dielectric Strength, V/mil	0149	365	440	400	530	630	500	510	475	500	500	500
Volume Resistivity, ohmcm	0257	2.5×10^{15}	5×10^{14}	1.8×10^{14}	5×10^{15}	4×10^{14}	—	—	—	10^{14}	10^{14}	10^{14}
Surface Resistivity, ohm	0257	—	2.9×10^{14}	7.8×10^{13}	—	—	—	—	—	—	—	—
Arc Resistance, s	0495	—	130	135	—	—	—	—	—	110	120	120
Dielectric Constant, dimensionless	0150											
10 ² Hz		4.16	4.2	4.4	—	—	—	—	—	—	—	—
10 ³ Hz		3.87	3.9	4.4	4.5	4.2	—	—	—	—	—	—
10 ⁶ Hz		3.35	3.5	4.0	3.7	3.4	—	—	—	3.75	3.8	3.8
Dissipation Factor, dimensionless	0150											
10 ² Hz		0.027	0.009	0.009	—	—	—	—	—	—	—	—
10 ³ Hz		0.026	0.012	0.012	0.020	0.019	—	—	—	—	—	—
10 ⁶ Hz		0.024	0.018	0.019	0.022	0.018	—	—	—	0.019	0.016	0.015

Glass Content Property	ASTM Test Method	Non-reinforced	NYLAFIL								NYPEL
			6-1/30 30%	G-1/30/EM 30%	G-10/40 40%	G-1/30/MS/5 30%	5-1/30 30%	J-1/30/EM 30%	J-10/40 40%	S-1/30 30%	6630 30%
Dielectric Strength, V/mil	0149	365	500	470	480	—	500	470	480	500	480
Volume Resistivity, ohmcm	0257	2.5×10^{15}	10^{16}	10^{16}	10^{15}	10^{16}	10^{16}	10^{16}	10^{15}	10^{17}	5.8×10^{15}
Surface Resistivity, ohm	0257	—	10^{17}	10^{17}	10^{16}	10^{17}	10^{17}	10^{17}	10^{16}	10^{18}	—
Arc Resistance, s	0495	—	100	100	100	—	400	100	100	110	—
Dielectric Constant, dimensionless	0150										
10 ² Hz		4.16	4.0	4.2	4.4	—	4.1	4.3	4.5	4.3	4.03
10 ³ Hz		3.87	3.8	4.0	4.3	—	4.0	4.1	4.4	4.2	3.94
10 ⁶ Hz		3.35	3.5	3.6	4.1	—	3.8	3.9	4.2	4.0	3.71
Dissipation Factor, dimensionless	0150										
10 ² Hz		0.027	0.022	0.023	0.009	—	—	—	—	0.007	0.006
10 ³ Hz		0.026	0.020	0.022	0.011	—	—	—	—	0.011	0.009
10 ⁶ Hz		0.024	0.017	0.018	0.018	—	—	—	—	0.014	0.013

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TABLE 3-57. ELECTRICAL PROPERTIES OF NYLON 6/10

Property	Glass Content	ASTM Test Method	THERMOCOMP		NYLAFIL					THERMOFIL		
			QF-1006 30%	QF-1008 40%	6-2/30 30%	6-12/40 40%	J-2/30 30%	J-12/40 40%	S-2/30 30%	N5-1500 15%	N5-3300 33%	N5-5000 50%
Dielectric Strength, V/mil		D 149	440	420	500	500	500	500	550	500	530	535
Volume Resistivity, ohmcm		D257	7.6×10^{15}	1.5×10^{15}	10^{14}	10^{15}	10^{14}	10^{15}	10^{17}	—	—	—
Surface Resistivity, ohm		Q257	1.5×10^{15}	6.8×10^{14}	10^{15}	10^{16}	10^{15}	10^{16}	10^{18}	—	—	—
Arc Resistance, s		D495	125	130	100	100	100	100	110	—	—	—
Dielectric Constant, dimensionless		D 150										
10^2 Hz			4.2	4.3	4.2	4.2	4.3	4.3	4.1	—	—	—
10^3 Hz			3.8	3.9	4.0	4.1	4.1	4.2	4.0	—	—	—
10^6 Hz			3.5	3.9	3.5	4.0	3.8	4.1	3.7	—	—	—
Dissipation Factor, dimensionless		D 150										
10^2 Hz			0.013	0.015	0.026	0.013	—	—	0.012	—	—	—
10^3 Hz			0.016	0.018	0.025	0.014	—	—	0.015	—	—	—
10^6 Hz			0.015	0.016	0.022	0.016	—	—	0.016	—	—	—

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TABLE 3-58. ELECTRICAL PROPERTIES OF NYLON 6/12

Property	ASTM Test Method	Nonreinforced	ZYTEL	
			77G-33NC10 33% GF	77G-43NC10 43% GF
Dielectric Strength, V/mil	D149	400		
Short time				
dry			520	500
100% RH			440	460
Step by step				
dry			490	480
100% RH	390	360		
Dielectric Constant, dimensionless	D150	3.6		
dry, 10^3 Hz			3.7	4.0
100% RH, 10^3 Hz			7.8	7.8
dry, 10^6 Hz			3.4	3.6
100% RH, 10^6 Hz	4.0	4.2		
Dissipation Factor, dry, dimensionless	D150	0.02		
10^3 Hz			0.024	0.027
10^6 Hz	0.02	0.016	0.017	
Volume Resistivity, ohm-cm	D257	10^{13} ^a		
dry			1×10^{15}	1×10^{15}
100% RH	3×10^{12}	2×10^{12}		
Surface Resistivity, ohm	D257			
dry			9×10^{14}	8×10^{14}
100% RH	6×10^{12}	5×10^{12}		

^a50% RH

TABLE 3-59. ELECTRICAL PROPERTIES OF RILSAN NYLON 11¹⁹

Glass Content Property	ASTM Test Method	BMN Non- reinforced	RILSAN				
			ZM 30%	ZM 2369 23%	ZM 4369 43%	ZM 30 Black W3 30%	ZM 30 Black TL 30%
Volume Resistivity, at 20° C and 65% RH, ohm•cm	D257	7.8×10^{13}	4.3×10^{14}	1.9×10^{13}	4.5×10^{13}	5.6×10^{12}	6.9×10^{12}
Surface Resistivity, at 20° C and 65% RH, ohm	D257	2.0×10^{14}	1.3×10^{12}	5.7×10^{11}	5.9×10^{12}	8.5×10^{11}	3.3×10^{12}
Dielectric Strength, (dry, 3 mm thickness), kV/mm	D 149	17	20	19	—	—	—

TABLE 3-60. ELECTRICAL PROPERTIES OF VESTAMID NYLON 12²¹

Glass Content Property	Measured According to IEC*	Test Method Equivalent ASTM	Standards BS	Conditioning†	VESTAMID	
					Standard Grades Unreinforced	L 1930 30%
Volume Resistivity, ohm•cm	IEC Publ. 93	0257	BS 2782 Part 21202 A	a	$>10^{15}$	8.5×10^{14}
				b	2×10^{14}	1×10^{14}
				c	7×10^{13}	8×10^{13}
				d	2×10^{13}	3×10^{12}
Surface Resistance, ohm	IEC Publ. 167	D257	BS 2782 Part 21203 A	a	$>10^{13}$	$>10^{13}$
				b		$>10^{13}$
				c	$>10^{13}$	8×10^{12}
				d	1×10^{12}	4×10^{11}
Dissipation Factor at 1000 Hz, dimensionless	IEC Publ. 250	D150	BS 2782 Part 21207 A	a	5×10^{-2}	4×10^{-2}
				d	17×10^{-2}	15×10^{-2}
Dielectric Constant at 1000 Hz, dimensionless	IEC Publ. 250	D150	BS 2782 Part 21207 A	a	3.6	4.0
				d	6.5	6.4
Tracking Index	IEC Publ. 112				500	500
Dielectric Strength, kV/mm [‡]	IEC Publ. 243				90	90

*IEC = International Electrotechnical Commission

† a: Measured on dry, freshly injection-molded test specimens (water content < 0.1%).

b: Conditioning: 23° C and 50% RH up to saturation.

c: Conditioning: 20° C and 65% RH up to saturation.

d: Conditioning: 20° C and 100% RH up to saturation.

‡ Electrode arrangement: ball 20 mm, sheet 50 mm, thickness of test specimen 0.5 mm.

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TABLE 3-61. PHYSICAL AND MECHANICAL PROPERTIES OF POLYCARBONATES

Glass Content Property	ASTM Test Method	POLYCARBAFIL																
		G-50120 20%	G-50/30 30%	G-50140 40%	G-50/20/ TF/12 20%	G-50/20/ TF/22 20%	G-50/20/ TF/44 20%	G-50/40/ TF/12 40%	G-50/40/ TF/22 40%	J-50/20 20%	J-50/30 30%	J-50/40 40%	J-50/20/ TF/12 20%	J-50/20/ TF/22 20%	J-50/30/ TF/12 30%	J-50/30/ TF/22 30%	S-50/20 20%	S-50/20/ TF/12 20%
Specific Gravity	0792	1.34	1.43	1.52	1.40	1.45	1.53	1.58	1.62	1.34	1.43	1.52	1.40	1.46	1.49	1.55	1.34	1.40
Specific Volume, in. ³ /lb		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Water Absorption, % 24 h equil. cont. immersion	0570	0.11 0.3	0.09 0.2	0.08 0.2	0.15 0.3	0.15 0.3	0.05 0.6	0.08 0.5	0.10 0.3	0.17 —	0.15 —	0.12 —	0.13 0.3	0.15 0.3	— —	0.10 —	0.15 0.4	0.13 0.3
Mold Shrinkage, in./in. 1/8 in. ave. section 1/4 in. ave. section	D955	0.002 0.002	0.002 0.002	0.002 0.002	0.002 0.003	0.003 0.004	0.003 0.004	0.002 0.003	0.002 0.003	0.002 0.004	0.002 0.003	0.001 0.002	0.002 0.003	— —	— —	0.002 0.003	0.002 0.003	0.002 0.003
Tensile Strength, psi -40° F 73° F 150° F 250° F	D638	— 18,500 — —	— 19,200 — —	21,500 20,000 — 18,000 ^c	— 17,000 — —	— 16,000 — —	— 14,000 — —	— 17,500 — —	— 17,000 — —	— 15,500 — 11,500 ^f	— 18,000 — 14,000 ^c	— 20,000 — 18,000 ^c	— 12,000 — —	— 10,000 — —	— 15,000 — —	— 13,500 — —	— 10,000 — 7,000 ^f	— 12,000 — —
Tensile Elongation, %	0638	2.2	1.8	1.4	3.0	3.0	1.8	1.2	1.5	2.0	1.5	1.2	3.0	3.0	1.8	1.2	1.0	3.0
Tensile Modulus, psi	D638	1,200,000	1,500,000	1,700,000	850,000	810,000	750,000	1,430,000	1,400,000	900,000	1,300,000	1,700,000	1,000,000	1,000,000	—	—	1,000,000	1,000,000
Flexural Strength, psi	0790	22,000	23,500	25,000	21,000	20,500	14,000	23,000	24,000	22,000	24,000	26,000	17,000	10,900	22,000	17,500	17,000	17,000
Flexural Modulus, psi	0790	800,000	1,050,000	1,250,000	750,000	730,000	—	—	—	800,000	1,000,000	1,200,000	700,000	540,000	—	—	750,000	700,000
Compressive Strength, psi	0695	18,000	18,500	19,000	15,500	14,500	9,000	15,500	14,000	—	—	17,000	15,000	11,700	—	—	15,000	15,000
Shear Strength, psi	0732	10,000	10,500	11,000	9,000	8,500	6,000	10,000	8,500	—	—	16,000	8,500	6,800	—	—	9,000	8,500
Impact Strength, Izod, ft•lb/in. notched 1/4 in. × 1/2 in. bar unnotched 1/4 in. × 1/2 in. bar	0256	3.0 9.0	— —	3.5 12.0	3.0 —	3.0 —	3.0 —	3.5 —	4.0 —	2.0 —	2.1 —	2.2 —	1.5 —	1.3 —	2.0 —	1.3 —	1.5 —	1.5 —
Tensile Impact Strength, Type "L" Specimen, ft•lb/in. ²	01822	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Taber Abrasion, CS-17 wheel, 1000-g load, mg/1000 cycles	01044	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Rockwell Hardness	0785	M85-95	—	M90-100	M90-100	M87-97	M63-73	M80-90	M75-85	M80	M80	M85	M75-85	M87-97	—	—	M75-85	M75-85
Fatigue Endurance Limit, at 2 × 10 ⁶ cycles, psi	0671	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Falling Dart Impact Strength, 1/8 in. thick, ft•lb		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Deformation Under Load, % 4000 psi, 73° F 4000 psi, 158° F	0621	0.10 0.12 ^c	— 0.11 ^d	— 0.10 ^d	— 0.12 ^d	— 0.12 ^d	— 0.20 ^d	— 0.10 ^d	— 0.10 ^d	— —	— —	— —	— 0.2 ^d	— 0.36 ^d	— —	— —	— 0.2 ^d	— 0.2 ^d

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TABLE 3-61. (cont'd)

Glass Content	ASTM Test Method	THERMOCOMP				LEXAN			MERLON	THERMOFIL			FIBERITE RTP		
		Unfortified Polycarbonate	DF-1004 20%	DF-1006 30%	DF-1008 40%	500 10%	3412 20%	3414 40%	9310 1090	R1000 10%	R2000 20%	R3000 30%	303 20%	305 30%	307 40%
Specific Gravity	D792	1.20	1.34	1.43	1.52	1.25	1.35	1.52	1.28	1.26	1.35	1.43	1.34	1.43	1.52
Specific Volume, in. ³ /lb		23.0	20.7	19.4	18.2	22.2	20.5	18.2	—	—	—	—	—	—	—
Water Absorption, % 24 h equil. cont. immersion	D570	0.15 0.35	0.09 0.19	0.07 0.18	0.06 0.16	0.12 0.31	0.16 0.29	0.12 0.23	0.15 —	— —	— —	— —	0.1 —	0.08 —	0.07 —
Mold Shrinkage, in./in. 1/8 in. ave. section 1/4 in. ave. section	D955	0.0060 0.007	0.0015 0.0025	0.0010 0.0020	0.0010 0.0020	— —	— —	— —	0.004–0.006 ^a —	— —	— —	— —	0.002 0.003	0.001 0.002	0.001 0.002
Tensile Strength, psi -40° F 73° F 150° F 250° F	D638	12,000 9,500 7,500 5,500	19,500 16,000 13,000 9,500	23,000 18,500 15,750 12,500	25,000 21,000 18,500 15,250	— 8,000 — —	— 16,000 — —	— 23,000 — —	— 10,500 — —	— 10,500 — —	— 15,500 — —	— 18,000 — —	— 17,000 — —	— 20,000 — —	— 21,000 — —
Tensile Elongation, %	D638	90	4–6	4–6	4–6	10–20	4–6	3–5	5	6	3	2	2.5	2.0	2.0
Tensile Modulus, psi	D638	340,000	1,000,000	1,375,000	1,700,000	4,500,000	860,000	1,680,000	—	—	—	—	1,200,000	1,400,000	1,700,000
Flexural Strength, psi	D790	13,500	25,000	28,000	30,000	15,000	19,000	27,000	18,000	—	—	—	19,000	23,000	26,000
Flexural Modulus, psi	D790	340,000	850,000	1,200,000	1,500,000	500,000	800,000	1,400,000	500,000	500,000	750,000	900,000	800,000	1,100,000	1,400,000
Compressive Strength, psi	D695	12,500	20,000	22,000	24,000	14,000	16,000	21,000	—	—	—	—	18,000	20,000	22,000
Shear Strength, psi	D732	10,000	8,600	9,400	9,900	8,500	10,000	11,000	—	—	—	—	—	—	—
Impact Strength, Izod, ft•lb/in. notched 1/4 in. x 1/2 in. bar unnotched 1/4 in. x 1/2 in. bar	D256	2.7 60	3.4 17	3.7 17	4.0 18	4–6 ^b 20–40 ^b	2.0 ^b 19 ^b	2.5 ^b 24 ^b	1.8 ^b —	2.5 —	2.5 —	2.3 —	1.4 11.0	1.7 11.0	2.2 12.0
Tensile Impact Strength, Type "L" Specimen, ft•lb/in. ²	D1822	300	120	210	260	—	30	35	—	—	—	—	—	—	—
Taber Abrasion, CS-17 wheel, 1000-g load, mg/1000 cycles	D1044	11	30	35	40	11	17	32	—	—	—	—	—	—	—
Rockwell Hardness	D785	M78	R118, M92	R118, M95	R118, M97	R124, M85	R122, M91	R119, M93	M80	—	—	—	R118	R119	R119
Fatigue Endurance Limit, at 2 x 10 ⁶ cycles, psi	0671	1,000	5,000	6,000	6,700	—	—	—	—	—	—	—	—	—	—
Falling Dart Impact Strength, 1/8 in. thick, ft•lb		> 125	—	—	—	> 125	2.5–5	3–6	—	—	—	—	—	—	—
Deformation Under Load, % 4000 psi, 73° F 4000 psi, 158° F	D621	0.2 0.3	— —	— —	— —	0.1 —	0.04 0.10	0.02 0.06	— —	— —	— —	— —	— —	— —	— —

^a Dimensions not given

^b 1/8 in. bar

^c at 170° F

^d at 122° F

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TABLE 3-62. LIMITING PRESSURE VELOCITY OF THERMOCOMP POLYCARBONATE⁷

LNP Series Code	PTFE Lubricant, wt%	Glass Content, wt%	Limiting PV (Journal Half Bearing)		
			10 ft/min	100 ft/min	1,000 ft/min
D 1000	—	—	750	500	—
DFL 4036	15	30	27,500	30,000	14,000
DFL 4038	15	40	20,000	22,500	10,000

TABLE 3-63. WEAR AND FRICTIONAL PROPERTIES OF THERMOCOMP POLYCARBONATE⁷

LNP Series Code	PTFE Lubricant, wt %	Glass Content, wt %	K -factor, ^{a,b} $\left(\frac{\text{in.}^3 \cdot \text{min}}{\text{ft} \cdot \text{lb} \cdot \text{h}}\right) \times 10^{-10}$	Coefficient of Friction ^a	
				Static (40 psi)	Dynamic (40 psi, 50 ft/min)
D 1000	—	—	2,500	0.31	0.38
DL 4030	15	—	75	0.09	0.15
DFL 4036	15	30	30	0.18	0.20
DFL 4038	15	40	45	0.20	0.23

^aMated against SAE 1040 steel.

^b K -factor values to be multiplied by 10^{-10} .

TABLE 3-64. ALLOWABLE WORKING STRESS LEVELS (psi) FOR LEXAN POLYCARBONATES²⁶

Temperature, °F	LEXAN 101, 141,191, Nonreinforced	LEXAN 500	LEXAN 3412 (20% Glass)	LEXAN 3414 (40% Glass)
<u>Continuous:^a</u>				
- 65	4200	5600	6000	7000
0	2300	3000	3900	5500
73	2000	2700	3500	5000
130	1600	2000	2500	4000
160	1000	1400	1700	3000
200	500	750	1000	2000
250	0	250	500	1000
<u>intermittent:^b</u>				
- 65	5200	6000	9500	12000
0	4200	4800	7500	10800
73	4000	4500	7000	10000
130	3500	4200	6300	8900
160	3200	3800	5600	7500
200	3000	3500	4700	6200
250	2500	3000	3700	5200
Fatigue Endurance Limit (i.e., 2.5×10^6 cycles)				
73	1000	3500	5500	7500

TABLE 3-65. THERMAL PROPERTIES OF POLYCARBONATES

Property	ASTM Test Method	THERMOCOMP				LEXAN			MERLON	THERMOFIL			FIBERITE RTP		
		Polycarbonate Nonreinforced	OF-1004 20%	OF-1006 30%	DF-1000 40%	500 10%	3412 20%	3414 40%	9310 10%	R-1000 10%	R-2000 20%	R-3000 30%	303 20%	305 30%	307 40%
Deformation Under Load, 4000 psi, 122° F, 24 h, %	0621	0.25	0.10	0.08	0.07	-	-	-	-	-	-	-	-	-	-
Deflection Temperature, °F 66 psi 264 psi	D648	270	305	305	305	295	300	310	-	-	-	-	300	300	300
		265	300	300	300	288	295	295	300	-	-	-	290	300	300
Thermal Conductivity, Btu/h•ft ² •°F/in.	Cenco	1.35	23	25	27	1.41	1.47	1.53	295	285	295	300	2.0	2.2	2.4
Coefficient of Linear Thermal Expansion, (in./in.•°F) x 10 ⁻⁵	0696	3.75	1.50	1.25	1.0	1.79	1.49	0.93	-	-	-	-	1.5	1.3	0.95
Flammability, in./min.	D635 UL Subj. 94	SE	SE	SE	SE	SE	SE	SE	SE	-	-	-	SE	SE	SE
		SE Gp 1	SE Gp 1	SE Gp 1	SE Gp 1	SEO	SE1	SE1	SEO	-	-	-	VE1	VE1	VE1
Oxygen Index	D2863	25.0	-	-	-	32.5	30.5	30.0	31	-	-	-	-	-	-

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TABLE 3-65. (cont'd)

Glass Content	ASTM Test Method	POLYCARBAFIL																
		G-50120 20%	G-50130 30%	G-50/40 40%	G-50/20/ TF/12 20% + TFE	G-50/20/ TF/22 20% ± TFE	G-501201 TF/44 20% + TFE	G-50/40/ TF/12 40% + TFE	G-501401 TF/22 40% + TFE	J-50120 20%	5-50/30 30%	J-50140 40%	J-50/20/ TF/12 20% ± TFE	J-50/20/ TF/22 20% ± TFE	J-50/30/ TF/12 30% TFE	J-50/30/ TF/22 30% + TFE	S-50/20 30%	S-50/20/ TF/12 20% ± TFE
Deformation Under Load, 4000 psi, 122 F, 24 h.	D621	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Deflection Temperature, F 66 psi 264 psi	D648	0.12	0.11	0.10	0.12	0.12	0.20	0.10	0.10	-	-	-	0	9.36	-	-	0.2	0.2
		305	-	310	305	300	305	310	305	-	-	305	295	-	-	-	295	295
Thermal Conductivity, Btu/h•ft ² • F/in.	Cenco	290	293	295	290	290	295	295	295	290	290	295	287	290	290	290	285	281
Coefficient of Linear Thermal Expansion, (in./in. • F) × 10 ⁻⁵	0696	1.8	-	1.2	-	-	-	-	1.2	-	-	1.2	1.4	-	-	1.1	1.4	1.4
Flammability, in./min.	D635	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	JL Subj. 94	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Oxygen Index	02863	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

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TABLE 3.66 FIFTEEN TEMPERATURE TIME BASED DATA OF DIVIDED RATES

Grade	Test Temp. °F	Initial Applied Stress, psi	App Modulus, $\text{psi} \times 10^3$						Time at Longest Test Point, h	
			1 h	10 h	100 h	1000 h	10000 h	At Longest Test Point		
Lexan 101, 141 (Unreinforced)	150	1500	100	80	225	210	197	190	12,200	
		2000	202	276	250	200	227	211	12,200	
	160	3000	225	200	193	190	189	189	11,000	
		4000	245	220	200	188	178	165	11,000	
	250	1500	240	215	190	180	170	145	11,000	
		2500	135	100	70	92	55	50	12,100	
		5000	150	105	70	92	55	40	12,100	
	Lexan 3414 (40% Glass)	150	3000	1040	800	750	750	750	750	12,200
			4000	960	870	750	750	750	750	12,200
160		5000	1020	1000	1000	1000	1000	1000	12,200	
		3000	1050	1015	980	960	950	900	11,000	
200		4000	940	870	820	800	760	700	11,000	
		5000	1080	970	900	850	850	830	11,000	
250		4000	1030	800	770	750	750	750	12,200	
		5000	1100	940	870	850	860	860	12,200	
		3000	1000	890	670	610	550	420	12,100	
		5000	1000	890	670	610	550	420	12,100	

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TABLE 3-67. ELECTRICAL PROPERTIES OF POLYCARBONATES

Property	ASTM Test Method	THERMOCOMP				LEXAN			POLYCARBAFIL		THERMOFIL			FIBERITE RTP		
		Nonreinforced Polycarbonate	OF-1004 20%	OF-1006 30%	OF-1008 40%	500 10%	3412 20%	3414 40%	G-50120 20%	G-50/40 40%	R-1000 10%	R-2000 20%	R-3000 30%	303 20%	305 30%	307 40%
Dielectric Strength, short time, V/mil	D 149	401	490	480	465	—	490	450	475	482	485	480	480	490	470	455
Volume Resistivity, ohm-cm	D257	2×10^{15}	6×10^{15}	6×10^{15}	6×10^{15}	5.6×10^{16}	4.6×10^{16}	4.0×10^{16}	1.5×10^{15}	1.5×10^{15}	—	—	—	10^{16}	10^{16}	10^{16}
Surface Resistivity, ohm	D257	—	—	—	—	—	—	—	7×10^{15}	7×10^{15}	—	—	—	—	—	—
Dielectric Constant, dimensionless	D150															
60 Hz		3.15	3.31	3.50	3.66	3.10	3.17	3.53	3.7	3.8	—	—	—	—	—	—
10^3 Hz		3.01	3.31	3.51	3.68	—	—	—	—	3.8	—	—	—	—	—	—
10^6 Hz		2.96	3.26	3.43	3.61	3.05	3.13	3.48	3.3	3.7	—	—	—	3.2	3.4	3.6
Dissipation Factor, dimensionless	D150															
60 Hz		0.0006	0.0008	0.0010	0.0012	0.0008 ^a	0.0009 ^a	0.0013 ^a	0.0060	0.003	—	—	—	—	—	—
10^3 Hz		0.0010	0.0011	0.0012	0.0014	—	—	—	—	0.002	—	—	—	—	—	—
10^6 Hz		0.0100	0.0079	0.0075	0.0072	0.0075	0.0073	0.0067	0.009	0.008	—	—	—	0.008	0.0075	0.007
Arc Resistance, tungsten electrodes, s	D495	120	120	120	120	120	120	120	—	—	—	—	—	120	120	120

^a power factor

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TABLE 3-68. PHYSICAL AND MECHANICAL PROPERTIES OF POLYESTERS

Property	ASTM Test Method	VALOX				CELANEX				
		310 Non-reinforced	310-SE0 Nonreinforced and Self-Extinguishing	420 30%	420-SE0 30%	2001 Non-reinforced	2011-SE0 Nonreinforced and Self-Extinguishing	3210-SE0 20%	3310-SE0 30%	3300 Reinforced 30%
Specific Gravity, 73° F	D792	1.31	1.41	1.52	1.58	1.31	1.41	1.56	1.67	1.52
Specific Volume, in. ³ /lb		21.1	19.6	18.1	17.5	21.1	19.6	17.8	16.6	18.2
Water Absorption, 73° F, % 24 h equil. cont. immersion	D570	0.08 0.34	0.08 0.38	0.06 0.26	0.07 0.25	0.09 0.27	0.09 0.27	0.07 0.25	0.07 0.25	0.07 0.40
Mold Shrinkage, (in./in.) x 10 ⁻³		17-23	17-23	2-4	2-4	17-23	17-23	2-6	2-6	2-6
Tensile Strength, psi	D638	8,000	8,900	17,300	17,000	8,200	9,400	15,000	17,000	17,000
Elongation at Break, %	D638	300	100	5	5	250-300	15	2-3	2	2
Flexural Strength, psi	D790	-	-	-	-	-	-	-	-	-
Flexural Modulus, psi	D790	340,000	380,000	1,200,000	1,200,000	330,000	400,000	1,100,000	1,400,000	1,100,000
Compressive Strength, 10% deformation, psi	D695	13,000	14,500	18,000	18,000	13,000	14,000	17,000	18,000	18,000
Shear Strength, psi	D732	7,700	7,700	8,900	9,000	-	-	-	-	-
Izod Impact Strength, ft•lb/in. notched unnotched	D256	12 No break	0.9 No break	2.2 15	1.8 15	1.0 No break	0.8 15.0	0.8 -	1.3 -	1.3 -
Coefficient of Friction, dimensionless self metal	D1894	0.17 0.13	0.16 0.14	0.16 0.14	0.16 0.14	0.12 0.10-0.13	0.12 0.10-0.13	0.12 0.10-0.13	0.12 0.10-0.13	0.16 0.12
Rockwell Hardness	0785	R117	R120	R118	R119	N78	N80	N90	N90	N90
Taber Abrasion, CS-17 wheel, 1000-g load, mg/1000 cycles	D1044	65	10.0	9.0	11.0	6	21	30	40	40

Property	ASTM Test Method	TENITE		THERMOCOMP			THERMOFIL	VERSEL	FIBERITE RTP		
		6P50 Non reinforced	6H91 20%	WF-1004 20%	WF-1006 30%	WF-1008 40%	E-3000 30%	1200 30%	1003 20%	1005 30%	1007 40%
Specific Gravity, 73° F	0792	1.31	1.53	1.43	1.52	1.62	1.52	1.53	1.45	1.53	1.63
Specific Volume, in. ³ /lb		-	-	18.5	17.5	16.5	-	18.2	-	-	-
Water Absorption, 73° F, % 24 h equil. cont. immersion	D570	0.09 0.30	- -	0.08 0.50	0.06 0.45	0.04 0.40	- -	0.06 -	0.070 -	0.070 -	0.080 -
Mold Shrinkage, (in./in.) x 10 ⁻³		16-28	2-5	3.5-5.5	3.0-4.5	2.5-3.5	2.0	-	4-5	3-4	2-3
Tensile Strength, psi	D638	8,000	18,500	17,500	19,500	22,000	17,500	18,000	16,500	18,000	21,500
Elongation at Break, %	D638	250	5	4-5	3-4	3-4	5	5	30	25	20
Flexural Strength, psi	D790	-	-	24,000	28,000	32,000	-	29,000	23,000	27,000	30,000
Flexural Modulus, psi	D790	350,000	1,250,000	1,100,000	1,350,000	1,600,000	1,200,000	1,200,000	800,000	1,200,000	1,500,000
Compressive Strength, 10% deformation, psi	D695	-	-	17,000	19,000	21,000	-	-	16,000	18,000	20,000
Shear Strength, psi	D732	-	-	-	-	-	-	-	-	-	-
Izod Impact Strength, ft•lb/in. notched unnotched	D256	0.8 No break	1.6 14	1.2-1.4 6-7	1.6-1.8 9-10	2.0-2.2 11-12	2.0 -	1.7 -	1.0 8.0	1.4 11.0	1.8 12.0
Coefficient of Friction, dimensionless self metal	D1894	0.19 0.23	- -	- -	- -	- -	- -	- -	- -	- -	- -
Rockwell Hardness	D785	68	90	R118, M82	R119, M84	R120, M86	-	M93	R117	R120	R120
Taber Abrasion, CS-17 wheel, 1000-g load, mg/1000 cycles	D1044	10	-	-	-	-	-	-	-	-	-

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TABLE 3-69. PHYSICAL AND MECHANICAL PROPERTIES OF FR-PET, 30% GLASS FILLED²⁹

Property	ASTM Test Method	B1030	B3030
Specific Gravity	D792	1.63	1.59
Tensile Strength, kgf/cm ²	D638	1,250-1,450	1,200-1,250
Elongation, %	D638	1.4-1.5	1.4-1.5
Flexural Strength, kgf/cm ²	D790	1,900-2,200	1,800-1,850
Flexural Modulus, (kgf/cm ²) x 10 ³	D790	95-100	80-90
Impact Strength, kgf•cm/cm	D256	9.0-13.5	4.5-5.0
Compressive Strength, kgf/cm ²	D695	1,400-1,500	1,300-1,400
Rockwell Hardness, M-scale	D785	95-100	95-100
Heat Distortion Temp., °C	D648	242	238
Thermal Expansion, (cm/cm•°C) x 10 ⁻⁵	D696	2.5	2.5
Thermal Conductivity, (cal/s•cm ² •°C/cm) x 10 ⁻⁴	C177	2.4	2.4
Water Absorption, %	D570	0.13	0.13

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TABLE 3-70. THERMAL PROPERTIES OF POLYESTERS

Glass Content	ASTM Test Method	VALOX				CELANEX				
		310 Non-reinforced	310-SE0 Nonreinforced and Self-Extinguish	420 30%	420-SE 30%	2001 Non-reinforced	2011-SE0 Nonreinforced and Self-Extinguish	3210-SE0 20%	3310-SE0 30%	3300 30%
Property										
Heat Deflection Temperature, °F 66 psi 264 psi	D648	310 130	325 160	420 415	420 415	310 130	354 135	435 392	442 416	442 416
Coefficient of Thermal Expansion, (in./in.·°F) x 10 ⁻⁵	D696	5.3	4.7	3.3	3.5	6.3	5.5	1.3-5.4	3-5.4	1.3-5.4
Flammability	D635 UL 94	SB SB	SE SE-0	SB SB	SE SE-0	- SB	- SE-0	- SE-0	- SE-0	- SB
Thermal Conductivity, Btu/h·ft ² ·°F/in.	C177	-	-	-	-	-	-	-	-	-
Deformation Under Load, 4000 psi, 122" F, 24 h, %	D621	-	-	-	-	-	-	-	-	-

Glass Content	ASTM Test Method	TENITE		THERMOCOMP			THERMOFIL	VERSEL	FIBERITE RTP		
		6P50 Non-reinforced	6H91 20%	WF-1004 20%	WF-1006 30%	WF-1008 40%	E-3000 30%	1200 30%	1003 20%	1005 30%	1007 40%
Property											
Heat Deflection Temperature, °F 66 psi 264 psi	D648	302 122	- 405	420 410	440 430	450 450	- 415	- 410	410 400	420 415	420 415
Coefficient of Thermal Expansion, (in./in.·°F) x 10 ⁻⁵	D696	-	-	1.35	1.20	1.05	-	-	2.0	1.4	1.2
Flammability	D635 UL 94	- -	- -	- 94HB	- 94HB	- 94HB	SB -	- -	B HB	B HB	B HB
Thermal Conductivity, Btu/h·ft ² ·°F/in.	C177	-	-	2.9	3.2	3.5	-	-	12	14	1.5
Deformation Under Load, 4000 psi, 122" F, 24 h, %	D621	-	-	0.7	0.6	0.4	-	-	-	-	-

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TABLE 3-71. ELECTRICAL PROPERTIES OF POLYESTERS

Glass Content Property	ASTM Test Method	VALOX				CELANEX							THERMOFIL	VERSEL	FIBERITE RTP		
		310 Non-reinforced	310-SEO Non-reinforced	420 30%	420-SEO 30%	2001 Non-reinforced	2011-SEO Non-reinforced	3210-SEO 20%	3310-SEO 30%	3300 30%	6P50 Non-reinforced	6H91 20%	E3000 30%	1200 30%	1003 20%	1005 30%	1007 40%
Dielectric Strength, 73° F and 50% RH, V/mil short time, 1/16 in. thickness short time, > 1/16 in. thickness	D149	590	750 ^a	750	750	600	560	600	600	700	540	485 ^a	740	530 ^a	500 ^a	500 ^a	500 ^a
		—	—	—	425	420	—	460	460	460	—	—	—	—	—	—	—
Dielectric Constant, dimensionless 10 ² Hz 10 ⁶ Hz	D150	3.3	3.3	3.8	3.8	3.2	3.2	3.8	3.9	3.7	3.16	—	3.7	—	—	—	—
		3.1	3.1	3.7	3.7	3.1	3.1	3.7	3.7	3.6	—	3.46	—	3.6	3.7	3.8	4.1
Dissipation Factor, dimensionless 10 ² Hz 10 ⁶ Hz	D150	0.002	0.003	0.002	0.002	0.0020	0.0020	0.0020	0.0020	0.0015	—	—	—	0.002	—	—	—
		0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.0200	0.023	0.019	—	0.016	0.014	0.015	0.015
Volume Resistivity, ohmcm x 10	D257	4.0	4.0	3.2	3.4	0.1	0.1	0.5	0.5	1.0	—	2.3	—	—	1.0	1.0	1.0
Arc Resistance, s	D495	190	63	130	80	192	130	135	146	130	—	—	—	130	140	130	120
Hot Wire Ignition, s	UL55	16	20	63	34	—	—	—	—	—	—	—	—	—	—	—	—

^a 0.125 in. specimen

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TABLE 3-72. ELECTRICAL PROPERTIES OF 30% GLASS-REINFORCED FR-PET²⁹

Property	ASTM Test Method	FR-PET	
		B1030	B3030
Dielectric Strength, kV/mm	D 149	32	34
Volume Resistivity, ohmcm	D257	1.5×10^{16}	4.8×10^{16}
Surface Resistivity, ohm	D257	5×10^{15}	6.1×10^{16}
Dielectric Constant, dimensionless			
60 Hz	D150	4.26	4.33
10^3 Hz	D150	4.20	4.30
10^6 Hz	D150	3.98	4.00
Power Factor, dimensionless			
60 Hz	D150	0.0027	0.0023
10^3 Hz	D150	0.0045	0.0068
10^6 Hz	D150	0.0160	0.0208
Arc Resistance, s	D495	90-120	90-120

TABLE 3-73. ELECTRICAL PROPERTIES OF FR-PET AFTER EXPOSURE TO HIGH TEMPERATURE-LONG PERIOD²⁹

Property	Blank	High Temperature Processing Condition		
		120°C x 3 h	160°C x 30 day	200°C x 30 day
Volume Resistivity, ohmcm	1.5×10^{16}	1.5×10^{16}	1.4×10^{16}	1.7×10^{16}
Dielectric Constant, 60 Hz, dimensionless	4.4	4.26	4.20	4.27
Power Factor, 60 Hz, dimensionless	2.3×10^{-3}	3×10^{-3}	1.9×10^{-3}	1.9×10^{-3}

TABLE 3-74. CHEMICAL RESISTANCE OF 30% GLASS-REINFORCED VALOX THERMOPLASTIC
POLYESTERS AFTER 30-DAY IMMERSION IN CHEMICAL ENVIRONMENTS³²

Reagent	Temperature °F	Valox 420		Valox 420-SEO	
		% of Original Strength	% Weight Gain	% of Original Strength	% Weight Gain
Strong Acids					
10% Hydrochloric Acid	73	89	0.1	90	0.0
10% Acetic Acid	73	89	0.1	89	0.1
10% Sulfuric Acid	73	97	0.1	90	0.1
36% Sulfuric Acid (battery acid)	73	97	0.1	96	0.1
36% Sulfuric Acid (battery acid)	150	84	1.1	79	0.9
Strong Bases					
10% Sodium Hydroxide	73	2	0.9	17	-0.1
Organic Solvents—little or no effects					
Isopropyl Alcohol	73	100	0	99	0
Isopropyl Alcohol + H ₂ O (50:50)	73	96	0.3	96	0.2
Methanol	73	91	0.5	93	0.4
Acetone	73	86	1.1	76	1.6
1,4 Butanediol	73	100	0	99	0
Ethyl Acetate	73	96	0.7	88	1.2
Toluene	73	95	0.5	88	0.6
Heptane	73	98	0.1	97	0.0
Chlorobenzene	73	86	1.1	76	1.6
Turpentine	73	91	1.3	78	2.0
Perclean	73	91	0.5	93	0.4
Organic Solvents—some plastication					
1,2 Dichloroethane	73	62	5.2	37	9.4
Methyl Ethyl Ketone	73	70	0.8	58	1.3
Methylene Chloride	73	54	13	34	16
Automotive Related Environments					
Ethylene Glycol (Prestone antifreeze)	73	100	0	93	0
Motor Oil (Shell Super X)	73	100	0.1	99	0.1
Gasoline (Shell Regular)	73	100	0	98	0
	140	93	0.6	90	0.5
Gasoline (Shell Premium)	73	100	0	99	0
	140	90	0.7	96	0.6
Transmission Fluid—Dexron (Quaker State)	73	100	0.1	98	0
	250	100	0.6	97	0.4
Power Steering Fluid (Delco)	73	100	0	93	0.1
	150	100	0.4	99	0
Brake Fluid (Delco Supreme #11)	73	100	0	98	0
	150	100	0.4	96	0.2
Aviation Fuel (Texaco Avjet A)	73	100	0	90	0

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TABLE 3-75. CHEMICAL RESISTANCE OF 30% GLASS-REINFORCED FR-PET²⁹

Chemicals	Change in Tensile Strength, %	Change in Weight, %	Dimensional Change, %		Change of Appearance	Judgment
			longitudinal	Transverse		
Acetic acid	0.0	+2.41	-0.13	-0.03	None	Resistible
Ethyl acetate	-7.6	+1.50	-0.10	0.00	None	Resistible
Butanol	+6.1	-0.09	-0.03	-0.03	None	Resistible
Benzene	+3.8	+1.07	-0.07	-0.03	None	Resistible
Formalin	+3.8	+0.13	-0.10	-0.13	None	Resistible
Carbon tetrachloride	+0.7	+0.05	-0.06	-0.06	None	Resistible
Solvent naphtha	-5.3	+4.0	-0.2	-0.1	None	Resistible
Methyl ethyl ketone	-12.1	+0.21	-0.13	-0.07	None	Resistible
Methyl cellosolve No. 14	-9.1	-0.04	-0.10	-0.16	None	Resistible
Lubricating oil	+4.5	+0.19	+0.03	0.00	None	Resistible

(Immersed one week at room temp.)

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TABLE 3-76. CHEMICAL RESISTANCE OF TENITE/POLYTEREPHTHALATE 20% GLASS FIBER REINFORCED THERMOPLASTIC POLYESTER³⁰

Reagent	Change Observed (25°C), %					
	7 Days		28 Days		6 Months	
	Weight	Thickness	Weight	Thickness	Weight	Thickness
Benzene	0.93	0.79	1.49	0.77	2.62	1.93
Heptane	0.19	0.29	0.05	0.25	0.04	0.11
Isooctane	0.02	-0.13	0.03	-0.03	0.02	-0.11
Toluene	0.62	0.40	0.75	0.66	1.88	1.19
Carbon tetrachloride	0.17	0.13	0.28	0.24	0.54	0.29
1,2-Dichloroethylene	5.41	2.91	8.95	4.12	18.62	1.64
Ethanol (100%)	0.02	0.00	0.07	-0.03	0.30	0.13
Ethanol (50%)	0.15	0.00	0.29	-0.03	0.44	0.05
Methanol	0.26	-0.26	0.51	-0.10	1.23	0.16
Phenol (5%)	3.01	2.11	4.61	2.84	7.97	4.41
Ethyl acetate	0.82	0.53	0.14	0.90	2.59	1.61
Dibutyl sebacate	0.03	0.00	0.07	-0.05	0.04	0.16
Bis(2-ethylhexyl) phthalate	0.01	0.00	0.01	0.05	0.04	0.11
Acetone	1.04	0.66	1.72	1.19	3.78	2.41
Aniline	2.16	1.71	3.26	2.35	5.50	3.64
Ethyl ether	0.16	0.13	0.30	0.16	0.74	0.42
N,N-Dimethylformamide	0.75	0.53	0.13	0.85	2.24	1.91
Deionized water	0.16	0.00	0.28	0.00	0.38	0.13
Alconox® detergent sol'n. (0.25%)	0.15	0.00	0.28	-0.37	0.37	-0.34
Ivory® soap sol'n. (1%)	0.15	0.10	0.27	-0.13	0.37	0.10
Brake fluid	-0.03	0.00	-0.05	-0.03	0.02	0.03
Cottonseed oil	0.01	0.00	0.01	-0.13	0.08	-0.13
Kerosine	0.02	0.00	0.02	0.00	0.03	-0.11
Mineral oil	0.02	0.13	0.03	0.13	0.04	-0.13
Olive oil	0.03	0.00	0.07	0.05	0.04	0.13
Transformer oil	0.02	-0.13	0.03	-0.03	0.05	-0.13
Turpentine	0.11	0.00	0.16	-0.02	0.25	0.08
Ammonium hydroxide (conc.)	0.18	0.00	0.35	-0.24	0.55	-0.10
Ammonium hydroxide (10%)	0.18	0.00	0.32	-0.03	0.45	-0.03
Sodium carbonate (20%)	0.13	0.00	0.23	-0.02	0.30	0.11
Sodium carbonate (2%)	0.15	0.00	0.27	-0.05	0.36	0.03
Sodium hydroxide (10%)	0.12	0.00	0.17	0.02	0.45	-0.56
Sodium hydroxide (1%)	0.15	0.00	0.27	-0.02	0.36	1.30
Sodium chloride (10%)	0.14	0.00	0.17	0.00	0.32	0.08
Acetic acid (glacial)	0.57	0.56	1.02	0.66	2.12	1.61
Acetic acid (5%)	0.15	0.00	0.27	-0.19	0.38	-0.16
Citric acid (10%)	0.16	0.00	0.29	0.05	0.36	0.11
Oleic acid (93%)	0.11	0.00	0.19	-0.08	0.28	-0.05
Hydrochloric acid (conc.)	0.12	0.00	0.17	-0.08	0.34	0.08
Hydrochloric acid (10%)	0.14	0.00	0.26	0.00	0.34	0.03
Nitric acid (conc.)	Disintegrates					
Nitric acid (40%)	0.15	0.00	0.29	-0.08	0.70	0.05
Nitric acid (10%)	0.14	0.00	0.26	-0.27	0.35	-0.19
Sulfuric acid (conc.)	Disintegrates					
Sulfuric acid (30%)	0.09	0.00	0.17	-0.05	0.23	0.05
Sulfuric acid (3%)	0.14	0.00	0.27	-0.03	0.36	0.18
Chromic anhydride (40%)	0.10	0.00	0.18	-0.08	0.18	-0.08
Hydrogen peroxide (28%)	0.19	0.13	0.31	0.05	0.41	0.05
Hydrogen peroxide (3%)	0.16	0.00	0.29	0.13	0.37	0.13
Sodium hypochlorite (3.5%)	0.15	0.00	0.28	-0.08	0.37	-0.08

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TABLE 3-77. PHYSICAL AND MECHANICAL PROPERTIES OF POLYETHERSULFONE³³

Property	Glass Content	ASTM Test Method	THERMOCOMP			
			J-1000 Nonreinforced	JF-1004 20%	JF-1008 40%	JFL-4036 15% TFE/30% FG
Specific Gravity		D 792	1.37	1.51	1.68	1.70
Specific Volume, in. ³ /lb		D 792	20.25	18.38	16.61	16.32
Mold Shrinkage, 1/8 in., in./in.		D955	0.007	0.003	0.0015	0.0015
Water Absorption, 24 h, %		D570	0.43	0.37	0.31	0.28
Tensile Strength, psi		D 638	12,200	18,000	22,000	18,000
Tensile Elongation, %		D638	—	3-4	3-4	3-4
Flexural Strength, psi		D 790	18,700	25,000	30,000	25,000
Flexural Modulus, psi		D 790	370,000	850,000	1,600,000	1,100,000
Izod Impact Strength, ft•lb/in. notched 1/4 in.		D256	1.6	1.4	1.6	1.5
Izod Impact Strength, ft•lb/in. unnotched 1/4 in.		D256	—	8.0	12.0	6.5
Tensile Impact, ft•lb/in. ²		D 1822	—	40.0	60.0	40.0
Rockwell Hardness		D674	M88	M98	M98	M96

TABLE 3-78. THERMAL PROPERTIES OF THERMOCOMP POLYETHERSULFONE³³

Property	Glass Content	ASTM Test Method	THERMOCOMP			
			J-1000 Nonreinforced	JF-1004 20%	JF-1008 40%	JFL-4036 15% TFE/30%
Heat Distortion Temperature at 264 psi, ° F		D648	395	410	420	410
Thermal Expansion, (in./in. • ° F) x 10 ⁻⁵		D696	3.1	2.0	1.6	1.9
Thermal Conductivity, Btu/h • ft ² • ° F/in.		C177	1.9	2.3	2.7	2.4
Flammability		UL	94V0	94V0	94V0	94V0

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TABLE 3-79. PHYSICAL AND MECHANICAL PROPERTIES OF POLYETHYLENES

Glass Content Property	ASTM Test Method	Low Density PE Non-reinforced	High Density PE Non-reinforced	THERMOCOMP			ETHOFIL						THERMOFIL		FIBERITE RTP		
				FF-1004 20%	FF-1006 30%	FF-1008 40%	G-90/20 20%	G-90/30 30%	G-90/40 40%	J-90/20 20%	J-90/30 30%	J-90/40 40%	F-1000 10%	F-3000 30%	703 20%	705 30%	707 40%
Specific Gravity	D792	0.910–0.925	0.941–0.965	1.10	1.17	1.28	1.09	1.18	1.28	1.09	1.18	1.28	1.04	1.18	1.1	1.18	1.28
Specific Volume, in. ³ /lb	D792	30.4–29.9	29.4–28.7	25.2	23.7	21.6	–	–	–	–	–	–	–	–	–	–	–
Water Absorption, % 24 h to saturation	D570	1.04 –	1.00–1.04 –	0.010 0.10	0.015 0.20	0.020 0.30	0.05 –	0.06 –	0.08 –	0.05 –	0.06 –	0.08 –	–	–	0.01 –	0.017 –	0.022
Mold Shrinkage, in./in. 1/8 in. ave. section 1/4 in. ave. section	D955	0.015 ^b 0.50	0.02–0.05 ^b –	0.0035 0.0045	0.0030 0.0040	0.0025 0.0035	0.003 0.004	0.003 0.004	0.002 0.003	0.004 0.005	0.003 0.005	0.003 0.005	–	–	0.003 0.004	0.003 0.0035	0.003 0.002
Tensile Strength, psi	D638	600–2,300	3,100–5,500	8,000	10,000	11,500	7,000	8,500	11,000	6,500	7,500	9,000	6,500	10,200	7,000	9,000	10,000
Tensile Elongation, %	D638	90–800	20–1,300	2–3	2–3	2–3	2.5	2.0	1.5	2.6	2.4	1.6	4	2	2.5	1.5	1.5
Flexural Strength, psi	D790	–	–	10,000	11,500	14,000	8,000	9,500	11,000	7,000	9,000	10,000	–	–	9,000	11,000	12,000
Flexural Modulus, psi	D790	600–800,000	1,000,000–600,000	600,000	900,000	1,100,000	600,000	800,000	900,000	500,000	700,000	800,000	400,000	850,000	550,000	800,000	1,000,000
Shear Strength, psi	D732	–	–	4,000	4,400	4,900	4,000	4,500	5,000	3,500	4,000	4,500	–	–	–	–	–
Izod Impact Strength, ft•lb/in. notched 1/4 in. bar unnotched 1/4 in. bar	D256	No break –	0.5–20.0 ^c –	1.0 4–5	1.1 8–9	1.3 11–12	2.5 –	3.0 –	3.5 –	1.2 –	1.3 –	1.5 –	1.6 ^a –	2.8 ^a –	1.2 4.2	1.3 4.5	1.4 5.0
Tensile Impact, ft•lb/in. ²	D1822	–	–	25	28	31	–	–	–	–	–	–	–	–	–	–	–
Compressive Strength, psi	D695	–	2,700–3,600	–	–	–	5,000	6,000	6,000	5,000	6,000	6,000	–	–	5,000	7,000	7,500
Rockwell Hardness	D785	R10	D60–D70	R80	R85	R90	R75–80	R80–90	R80–90	R75–85	R80–90	R80–90	–	–	R65	R75	R85

^a 1/8 in. bar

^b linear

^c 1/2 in. bar

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TABLE 3-80. EFFECT OF 1/8 in. GLASS CONTENT ON VARIOUS ROTATIONAL MOLDED POLYETHYLENE PROPERTIES³⁵

Resin	Glass, wt %	Melt Index	Density	Tear Resistance, lb/in.	Tensile Strength, psi	Ultimate Elongation, %	Yield Strength, psi	Flexural Strength, psi	Flexural Modulus, psi	Secant Modulus, psi
PEP-750	0	7.7	0.950	473	3150	41	3030	4520	145,000	98,300
PEP-750	5	4.2	0.978	663	2970	12	2970	5170	191,000	135,000
PEP-750	10	4.1	1.005	835	3390	5	3390	5740	240,000	159,000
PXEP-4649	0	4.1	0.968	814	4020	40	3780	5680	225,000	138,000
PXEP-4649	5	3.3	0.993	802	3520	5	3520	6310	262,000	173,000
PEP-530	0	9	0.923	520	1400	220	1360	1090	29,300	26,000
PEP-530	5	6.5	0.955	625	1600	45	1420	1820	50,400	39,000
PEP-530	10	—	—	619	1680	34	1540	2050	97,000	—
PEP-320	0	1.00	0.923	480	1340	435	—	1100	19,000	20,000
PEP-320	5	0.71	—	550	1330	87	1140	1200	29,800	23,100
PEP-320	10	0.65	—	566	1370	39	1210	1480	39,500	38,000
PEP-350	0	11	0.919	400	1300	150	1090	1400	20,800	18,000
PEP-350	5	6	0.942	515	1230	71	1120	1400	35,400	30,600
PEP-350	10	—	0.990	520	1280	31	1180	1510	39,200	35,500
PXEP-4690	0	23	0.915	428	1160	529	977	874	18,700	16,000
PXEP-4690	5	20	0.947	443	1180	61	1020	1100	30,800	25,900
PXEP-4690	10	15	0.974	484	1210	41	1120	1470	44,200	35,400

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TABLE 3-81. THERMAL PROPERTIES OF POLYETHYLENES

Property	Glass Content	ASTM Test Method	Low Density Nonreinforced	High Density Nonreinforced	THERMOCOMP			ETHOFIL						THERMOFIL		FIBERITE RTP		
					FF-1004 20%	FF-1006 30%	FF-1008 40%	G-90/20 20%	G-90/30 30%	G-90/40 40%	J-90/20 20%	J-90/30 30%	J-90/40 40%	F-1000 10%	F-3000 30%	703 20%	705 30%	707 40%
Heat Distortion Temperature, °F 66 psi 264 psi		D648	100–121	140–190	265	270	270	265	265	265	250	255	255	–	–	260	265	270
			90–105	110–130	250	260	260	260	260	260	240	250	250	240	260	240	250	260
Thermal Conductivity, Btu/h•ft ² •°F/in.		C177	–	–	2.4	2.6	2.8	–	–	–	–	–	–	–	–	2.3	2.5	2.7
Coefficient of Linear Thermal Expansion, (in./in.•°F) x 10 ⁻⁵		D696	–	7.23	3.0	2.7	2.4	2.7	2.2	1.7	2.3	1.9	1.6	–	–	2.8	2.7	2.5
Flammability		D635 UL Subj. 94	–	–	–	–	–	–	–	–	–	–	–	–	–	B	B	B
			–	94HB	94HB	94HB	–	–	–	–	–	–	–	–	–	94HB	94HB	94HB

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TABLE 3-82. ELECTRICAL PROPERTIES OF POLYETHYLENE

Property	ASTM Test Method	Low Density	High Density	ALATHON			ETHOFIL		FIBERITE RTP		
				G-0530 30%	7050 20%	7050 15%	G-90/20 20%	G-90/40 40%	703 20%	705 30%	707 40%
Dielectric Strength (short time, 1/4 in. electrode), V/mil	D149	450–1000	450–500	580	600	620	700	600	500	500	500
Dielectric Constant, dimensionless	D150										
10 ² Hz		2.25–2.35	2.30–2.35	3.40	3.14	2.99	2.6	2.9	–	–	–
10 ³ Hz		2.25–2.35	2.30–2.35	3.26	3.05	3.02	2.6	2.9	–	–	–
10 ⁶ Hz		2.25–2.35	2.30–2.35	3.16	3.01	2.99	2.6	2.8	2.7	2.7	2.8
Dissipation Factor, dimensionless	D150										
10 ² Hz		–	–	0.0257	0.0226	0.007 1	0.00 1	0.001	–	–	–
10 ³ Hz		<0.0005	<0.0005	0.0 176	0.0 134	0.0035	0.00 1	0.001	–	–	–
10 ⁶ Hz		<0.0005	<0.0005	0.0008	0.0006	0.0006	0.00 1	0.001	0.007	0.008	0.008
Volume Resistivity, ohmcm	D257	> 10 ¹⁶ at 50% RH	> 10 ¹⁶ at 50% RH	1.15 x 10 ¹⁵	1.6 x 10 ¹⁵	3.2 x 10 ¹⁵	10 ¹⁵	10 ¹⁶	10 ¹⁶	10 ¹⁶	10 ¹⁶
Surface Resistivity, ohm		–	–	–	–	–	10 ¹⁵	10 ¹⁶	–	–	–
Arc Resistance, s	D495	–	180						140	140	140

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TABLE 3-83. PHYSICAL AND MECHANICAL PROPERTIES OF MODIFIED POLYPHENYLENE OXIDE

Glass Content Property	ASTM Test Method	NORYL					THERMOCOMP			THERMOFIL		
		731 Non-reinforced	GFN2 20%	GFN3 30%	SE1-GFN2 20%	SE1-GFN3 30%	ZF-1004 20%	ZF-1006 30%	ZF-1008 40%	L-1000 10%	L-2000 20%	L-3000 30%
Specific Gravity	D792	1.06	1.21	1.27	1.30	1.36	1.20	1.28	1.38	1.11	1.21	1.27
Specific Volume, in. ³ /lb	—	26.2	22.9	21.9	21.4	20.4	22.9	21.8	20.1	—	—	—
Water Absorption, % 24 h, 73° F to saturation, 90° F	D570	0.066 —	0.06 —	0.06 —	0.06 —	0.06 —	0.06 0.13	0.06 0.11	0.06 0.09	— —	— —	— —
Mold Shrinkage, (in./in.) x 10 ⁻³	D1299	5-7	2-4	1-3	2-4	1-3	0.002-0.003 ^a	0.001-0.002 ^a	0.001-0.002 ^a	—	—	—
Tensile Strength, psi at 73° F at 200° F	D638	9,600 6,500	14,500 10,600	17,000 13,500	14,500 10,000	17,800 11,200	16,000 —	18,500 —	19,500 —	12,000 —	14,000 —	17,500 —
Elongation at Break, %	D638	60	4-6	4-6	4-6	4-6	3-4	3-4	3-4	6	5	4
Tensile Modulus, psi at 73° F at 200° F	D638	355,000 230,000	925,000 750,000	1,200,000 1,110,000	925,000 750,000	1,200,000 1,000,000	—	—	—	—	—	—
Flexural Strength, psi at 73° F at 200° F	D790	13,500 7,300	18,500 13,500	20,000 18,000	18,500 13,200	20,000 14,400	21,000 —	23,000 —	25,000 —	—	—	—
Flexural Modulus, psi at 73° F at 200° F	D790	360,000 260,000	750,000 590,000	1,100,000 1,000,000	750,000 575,000	1,100,000 863,000	800,000 —	1,150,000 —	1,250,000 —	720,000 —	800,000 —	1,200,000 —
Compressive Strength, 10% deformation, psi	D695	16,400	17,600	17,900	17,600	17,900	—	—	—	—	—	—
Shear Strength, psi	D732	10,500	10,400	10,600	10,400	10,600	10,000	10,500	11,000	—	—	—
Creep, 300 h at 73° F and 2000 psi, % strain	D674	0.63	0.33	0.20	0.33	0.20	—	—	—	—	—	—
Izod Impact Strength, 1/8 in. bar, at 73° F	D256	5.0	2.3	2.3	2.3	2.3	1.7 ^b	1.7 ^b	1.5 ^b	1.1	1.2	1.4
Tensile Impact "L" Type Bars, ft•lb/in. ²	D1822	170	60	50	60	50	—	—	—	—	—	—
Rockwell Hardness	D785	R119	L106	L108	L106	L108	M90	M93	M94	—	—	—
Taber Abrasion, CS-17 wheel, 1000-g load, mg/1000 cycles	D1044	20	35	35	—	—	—	—	—	—	—	—
Fatigue Endurance Limit, 2 x 10 ⁶ cycles, psi	D671	2,500	4,000	5,000	—	—	—	—	—	—	—	—

^a 1/8 in. and 1/4 in. average section

^b 1/4 in. bar

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TABLE 3-84. THERMAL PROPERTIES OF MODIFIED POLYPHENYLENE OXIDE

Glass Content Property	ASTM Test Method	NORYL					THERMOCOMP			THERMOFIL		
		731 Non- reinforced	GFN2 20%	GFN3 30%	SE1-GFN2 20%	SE1-GFN3 30%	ZF-1004 20%	ZF-1006 30%	ZF-1008 40%	L-1000 10%	L-2000 20%	1-3000 30%
Deformation Under Load, at 122" F and 2000 psi, %	0621	0.30	0.20	0.12	0.30	0.25	0.20	0.13	0.08	--	--	
Heat Deflection Temperature, "F at 66 psi at 264 psi	0648	279	293	317	280	285	295	320	325	275	280	300
		265	290	300	270	275	290	310	315	--	--	
Thermal Conductivity, Btu/h•ft ² •°F/in.	C177	1.50	1.15	1.10	1.15	1.10	1.1	1.2	1.3	--	--	
Coefficient of Thermal Expansion, -20" to 150" F, (in./in.) x 10 ⁻⁵	0696	3.3	2.0	1.4	2.0	1.4	2.0	1.4	1.0	--	--	
UL Bulletin No. 94		94HB	94HB	94HB	94V0	94V0	94HB	94HB	94HB	--	--	
Flammability, 1/8 in. x 1/2 in. x 5 in.		--	--	--	--	--	--	--	--	SE	SE	SE
Continuous-Use Rating, mechanical w/impact, "C		90	90	90	--	--	--	--	--	--	--	
Continuous-Use Rating, mechanical and electrical w/o impact, "C		105	90	90	--	--	--	--	--	--	--	

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TABLE 3-85. ELECTRICAL PROPERTIES OF MODIFIED POLYPHENYLENE OXIDE

Glass Content Property	ASTM Test Method	NORYL					THERMOFIL		
		731 Non- reinforced	GFN2 20%	GFN3 30%	SE1-GFN2 20%	SE1-GFN3 30%	L-1000 10%	L-2000 20%	L-3000 30%
Dielectric Constant, 50% RH and 73" F, dimensionless 60 Hz	D150	2.65	2.86	2.93	2.98	3.15	—	—	—
		2.64	2.85	2.92	2.95	3.11	—	—	—
Dissipation Factor, 50% RH and 73" F, dimensionless 60 Hz	D150	0.0004	0.0008	0.0009	0.0016	0.0020	—	—	—
		0.0009	0.0014	0.0015	0.0017	0.0021	—	—	—
Volume Resistivity, dry and 73" F, ohm • cm	0257	10 ¹⁷	10 ¹⁷	10 ¹⁷	10 ¹⁷	10 ¹⁷	—	—	—
Surface Resistivity, ohm	D257	10 ¹⁶	10 ¹⁷	10 ¹⁷	10 ¹⁷	10 ¹⁷	—	—	—
Dielectric Strength, 1/8 in. sample, V/mil	D149	550	420	550	600	530	450	470	510
Arc Resistance, tungsten electrodes, s	0495	75	70	120	70	120			

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TABLE 3-86. PHYSICAL AND MECHANICAL PROPERTIES OF POLYPHENYLENE SULFIDE

Glass Content Property	ASTM Test Method	THERMOCOMP				RYTON		FIBERITE RTP			
		Non- fortified PPS	OF-1006 30%	OF-1008 40%	OFL-4036 30% with 15% TFE Lub	Ryton R4 40%	Ryton B PTFE/40%	1303 20%	1305 30%	1307 40%	1378 30%, 15% TFE
Specific Gravity	0792	1.34	1.56	1.65	1.67	1.6	1.75	1.44	1.53	1.62	1.64
Mold Shrinkage, 1/8in., in./in.	0955	0.010	0.002	0.001	0.00	—	—	0.003	0.002	0.001	0.002
Water Absorption, 24 h, %	0570	0.20	0.04	0.02	0.03	0.05	0.03	0.02	0.02	0.02	0.02
Tensile Strength, psi	0638	10,800	20,000	23,000	19,000	19,500	15,000	14,000	17,000	20,000	20,000
Elongation, %	0638	3-4	3-4	3-4	3-4	1.3	3	1.4	1.3	1.3	—
Flexural Strength: psi	0790	20,000	29,000	32,000	24,000	29,000	22,400	20,000	28,000	30,000	25,000
Flexural Modulus, psi x 10 ⁶	0790	0.6	1.6	1.8	1.3	1.7	1.4	1.1	1.4	1.6	1.4
Izod Impact Strength, ft•lb/in. notched 1/4in. unnotched 1/4in.	0256	0.3 3-4	1.4 8-9	1.5 11-12	1.1 6-7	1.4 ^a 8"	1.3 —	1.2 3.0	1.4 6.0	1.4 7.0	1.2 4.0
Wear Factor K, Equilibrium (in. ³ •min/ft•lb•h) x 10 ⁻¹⁰	LNP	540	—	—	110	—	—	—	—	—	105 ^b
Coefficient of Friction, dimensionless static at 40 psi dynamic at 50 fpm, 40 psi	LNP	0.30 0.24	— —	— —	0.17 0.15	— —	— —	— —	— —	— —	0.15 0.14 ^b
Compressive Strength: psi	1695-69	—	—	—	—	21,000	9,200	22,500	24,000	25,000	25,000
Rockwell Hardness	1785-65	—	—	—	—	R123	—	R121	R122	R123	R118

^a 1/8in. specimen^b On thrust washer apparatus, at 300 fpm against steel, 1141 RYEX, hardness 18-22, Rockwell C and 12-16 pin. finish, at 8500 PV.

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TABLE 3-87. EFFECT OF THERMAL AGING OF RYTON R-4
RESIN AT 450° F IN AIR ³⁸

Exposure Time, h	Flexural Strength, psi x 10 ⁴	Tensile Strength, psi x 10 ⁴
0	29	1.9
700	24	1.2
1,500	1.9	1.2
3,000	1.8	1.2
5,000	1.7	1.2
7,200	1.3	1.1
9,400	0.9	0.7

TABLE 3-88. THERMAL PROPERTIES OF POLYPHENYLENE SULFIDE

Glass Content Property	ASTM Test Method	THERMOCOMP				RYTON		FIBERITE RTP			
		PPS Non-reinforced	OF-1006 30%	OF-1008 40%	OFL-4036 30% 15% TFE	Ryton R4 40%	Ryton B PTFE/40%	1303 20%	1305 30%	1307 40%	1378 30%, 15% TFE
Heat Distortion Temperature, °F 264 psi	D648	278	500	505	500	500	500	500	500	500	500
Coefficient of Linear Thermal Expansion, (in./in. • °F) x 10 ⁻⁵	D696	3.0	1.3	1.1	1.5	2.5 ^a	2.3	1.6	1.4	1.2	2.0
Thermal Conductivity, Btu/h • ft ² • °F/in.	C177	2.0	2.8	3.1	2.7	2.0	2.7	2.1	2.1	2.2	2.7
UL Flammability		94 V0	94 V0	94 V0	94 V0	V0	—	VE0	VE0	VE0	VE0
Specific Heat, 24 h at 25° C, Btu/lb • °F		—	—	—	—	0.25	—	—	—	—	—

^a-30° C to +30° C determined by DuPont TMA instrument.

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TABLE 3-89. ELECTRICAL PROPERTIES OF POLYPHENYLENE SULFIDE

Property	Glass Content	ASTM Test Method	FIBERITE RTP					RYTON R4, 40%
			Nonre-inforced	1303 20%	1305 30%	1307 40%	1378 30%, 15% TFE	
Dielectric Strength, V/mil ^a		D149-64	380	350	350	350	350	350
Dielectric Constant, 25°C, dimensionless		D150-70	—	—	—	—	—	3.9
10 ³ Hz			3.1	3.5	3.5	3.0	3.8	3.8
10 ⁶ Hz								
Dissipation Factor, 25°C, dimensionless		D150-70	—	—	—	—	—	0.0013
10 ³ Hz			0.0009	0.001	0.001	0.001	0.0012	—
10 ⁶ Hz								
Volume Resistivity, 2 min, ohm-cm		D257-66	10 ¹⁶	10 ¹⁶	10 ¹⁶	10 ¹⁶	10 ¹⁶	4.5 x 10 ¹⁶
Arc Resistance, s		D495	20	120	120	120	50	—

^aTransformer oil, 500 V/s rate of increase

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TABLE 3-90. PHYSICAL AND MECHANICAL PROPERTIES OF POLYPROPYLENES

Property	ASTM Test Method	Glass Content	Non-reinforced	THERMOCOMP			PROFIL						PROFAX				THERMOFIL						FIBERITE RTP											
				MF-1004 H.S. 20%	MF-1006 H.S. 30%	MF-1008 H.S. 40%	G-60/20 20%	G-60/30 30%	G-60/40 40%	J-60/20 20%	J-60/30 30%	J-60/40 40%	J-60/20/E 20%	J-60/30/E 30%	J-60/40/E 40%	PC-633 10%	PC-307 20%	PC-304 30%	65F3 40%	P-1000 10%	P-2000 20%	P-3000 30%	P-4000 40%	P1-1000 10% *	P1-2000 20%	P1-3000 30%	P1-4000 40%	PSE-2000 20%	103CC 20%	105CC 30%	107CC 40%	103 20%	105 30%	107 40%
Specific Gravity	D792		0.9	1.04	1.13	1.22	1.04	1.13	1.22	1.04	1.13	1.22	1.04	1.12	1.20	0.97	1.04	1.11	1.23	0.96	1.04	1.13	1.22	0.96	1.04	1.13	1.22	1.34	1.05	1.13	1.23	1.05	1.13	1.23
Specific Volume, in. ³ /lb	D792		—	26.6	24.5	22.7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
Water Absorption, % 24 h equil. cont. immersion	D570		—	0.01	0.03	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.03	0.03	0.03	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
			—	0.02	0.06	0.10	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
Mold Shrinkage, in./in. 1/8 in. ave. section 1/4 in. ave. section	D955		—	0.0040	0.0040	0.0035	0.003	0.003	0.002	0.004	0.004	0.003	0.003	0.003	0.002	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
			—	0.0045	0.0045	0.0040	0.004	0.004	0.003	0.005	0.005	0.004	0.004	0.004	0.003	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
Tensile Strength, psi 73° F 120° F 140° F	D638		3,000–5,000	9,100	9,800	10,500	7,500	8,000	9,000	6,000	7,000	7,500	11,500	13,000	14,000	5,300 ^a	5,100 ^a	5,000 ^a	4,900 ^a	5,500 ^c	6,500 ^a	7,400 ^a	8,000 ^a	7,500 ^a	12,000 ^a	13,500 ^a	14,500 ^a	5,900 ^a	12,000	14,000	16,000	7,200	7,800	8,400
Tensile Elongation, %	D638		200–700	2–3	2–3	1–2	2.2	2.1	2.0	3.0	2.5	2.0	2.8	2.3	1.8	—	—	—	—	3.0	2.5	2.0	1.5	2.5	2.5	2.0	1.5	1.3	2.5	2.5	2.5	2.5	2.5	1.5
Tensile Modulus, psi x 10 ³ 73° F 120° F 140° F	D638		100–200	600	850	1,100	750	900	1,100	700	800	1,000	700	850	1,100	—	—	—	—	—	—	—	—	—	—	—	—	—	730	1,000	1,300	520	730	950
Flexural Strength, psi	D790		5,000–8,000	11,000	12,000	12,500	10,000	10,500	11,000	7,000	8,500	9,500	14,000	16,000	18,000	—	—	—	—	—	—	—	—	—	—	—	—	—	14,000	18,000	19,000	8,600	9,900	10,500
Flexural Modulus, psi x 10 ⁶	D790		1.2–2.7	0.6	0.8	1	0.55	0.7	0.9	0.5	0.6	0.75	0.65	0.8	1	0.33 ^b	0.39 ^b	0.47 ^b	0.54 ^b	0.4	0.54	0.76	0.8	0.4	0.54	0.76	0.8	0.48	0.55	0.7	0.9	0.52	0.73	0.95
Compressive Strength, psi	D695		3,700–8,000	7,700	8,500	9,800	6,500	7,000	7,000	6,500	7,000	7,000	6,800	7,300	7,500	—	—	—	—	—	—	—	—	—	—	—	—	9,700	12,000	13,000	7,500	8,400	8,900	
Izod Impact Strength, ft•lb/in. notched 1/4 in. x 1/2 in. bar unnotched 1/4 in. x 1/2 in. bar	D256		0.5–20.0	1.4	1.6	1.8	3.5	3.8	4.0	0.8	1.0	1.2	1.3	1.5	1.7	0.54 ^a	0.48 ^a	0.45 ^a	0.4 ^a	1.0 ^a	1.2 ^a	1.2 ^a	1.4 ^a	1.2 ^a	1.5 ^a	1.8 ^a	2.5 ^a	0.9 ^a	1.8	1.9	2.0	1.2	1.3	1.4
			—	6–7	5–6	4–5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	11.0	12.0	13.0	4.5	4.5	3.0	
Rockwell Hardness	D785		R50–110	M49, R111	M57, R111	M59, R111	R105–115	R105–115	R105–115	R100–110	R105–115	R105–115	R100–110	R105–115	R105–115	R98	R99	R99	R98	—	—	—	—	—	—	—	—	—	R93	R98	R105	R90	R95	R102

^a1/8 in. bar
^b1%secant, 1/8 in. specimen
^cat yield 1/8 in. specimen

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TABLE 3-91. COMPARISON OF PROPERTIES OF COUPLED GLASS-REINFORCED POLYPROPYLENES WITH UNREINFORCED POLYPROPYLENES⁴⁰

Property	Glass Content	Test Method	Propathene G X 543M Propylene Homopolymer Nonreinforced	Propathene PXC 8639		
				Polypropylene 10%	Polypropylene 20%	Polypropylene 30%
Specific Gravity			0.905	0.963	1.033	1.115
Flexural Modulus, GN/m ²		ASTM D790-70	1.7	2.5	3.65	5.1
Tensile Strength at 5 cm/min, MN/m ²		ASTM D638-64T(B)	34.0	56.0	75.0	100.0
Notched Impact Strength at 23° C, J		BS 2782 306A	1.3	1.4	1.6	1.8
Coefficient of Linear Thermal Expansion, °C ⁻¹			11 x 10 ⁻⁵	4 x 10 ⁻⁵	3 x 10 ⁻⁵	2 x 10 ⁻⁵
Heat Distortion Temperature at 18.6 kg/cm ² , °C		ASTM D648	70	138	152	155

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TABLE 3-92. EFFECT OF ADHESIVE ACID COMONOMER CONTENT ON THE MECHANICAL PROPERTIES OF 15% GLASS FIBER REINFORCED IMPACT PROPYLENE/ETHYLENE/ACID TERPOLYMERS⁴¹

Adhesive Acid Monomer Content	Gardner Impact Energy, in • lb	Secant Flexural Modulus, psi	Tensile Strength at Yield, psi
None	91 ± 2	183,000	3,220
Low	84 ± 3	255,000	4,070
Medium	74 ± 3	280,000	4,670
High	3 ± 1	419,000	7,566

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TABLE 3-93. TENSILE PROPERTIES OF INJECTION MOLDED POLYPROPYLENE AT 23° AND 80° C (REF. 42)

Resin	Glass, wt % ^a	at 23° C (73° F)		at 80° C (176° F)	
		Strength, psi	Modulus, psi	Strength, psi	Modulus, psi
Pro-Fax 6324 ^b	0	4,600	190,000	2,000	50,000
Pro-Fax PC-072 ^c	10	8,055	442,000	4,200	290,000
Pro-Fax PC-072	20	11,865	672,000	7,000	550,000
Pro-Fax PC-072	30	13,893	1,000,000	8,000	670,000
Pro-Fax PC-072	40	15,695	1,262,000	9,500	960,000

^aOwens-Corning Fiberglas OCF-885AA glass fibers

^bHercules, Inc., special resin for glass reinforcement

^cHercules, Inc.

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TABLE 3-94. EFFECT OF ACID COMONOMER CONTENT ON THE MECHANICAL PROPERTIES OF 15% GLASS FIBER REINFORCED IMPACT PROPYLENE/ETHYLENE/ACID TERPOLYMERS⁴¹

Adhesive Acid Monomer Content	Heat Deflection Temperature at 264 psi, °F
Non	161 ± 10
Low	189 ± 10
Medium	209 ± 10
High	235 ± 10

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TABLE 3-96. ELECTRICAL PROPERTIES OF POLYPROPYLENE⁴³

Property	Glass Content	ASTM Test Method	Non-reinforced	PROFIL		FIBERITE RTP					
				G-60/20 20%	G-60/40 40%	103CC 20%	105CC 30%	107CC 40%	103 20%	105 30%	107 40%
Dielectric Strength, V/mil short time		D149	500-660	450	300	520	500	500	530	520	510
				350	250	-	-	-	-	-	-
step by step			450-650								
Volume Resistivity, ohm • cm		D257	> 10 ¹⁶	10 ¹⁶	10 ¹⁶	10 ¹⁶	10 ¹⁵	10 ¹⁵	10 ¹⁶	10 ¹⁵	10 ¹⁵
Surface Resistivity, ohm		D257	-	10 ¹⁷	10 ¹⁷	-	-	-	-	-	-
Dielectric Constant, dimensionless		D150	2.2-2.6	2.3	2.5	-	-	-	-	-	-
				2.2	2.5	-	-	-	-	-	-
				2.2	2.5	2.6	2.7	2.8	2.8	2.9	3.2
Dissipation Factor, dimensionless		D150	< 0.005	0.002	0.002	-	-	-	-	-	-
				0.002	0.002	-	-	-	-	-	-
				0.004	0.003	0.001	0.001	0.002	0.001	0.001	0.002
Arc Resistance, s		D495	136	-	-	130	125	120	123	120	102

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TABLE 3-97. PHYSICAL AND MECHANICAL PROPERTIES OF POLYSTYRENE

Property	ASTM Test Method	General Purpose Flame Retardant Nonreinforced	THERMOCOMP			STYRAFIL						THERMOFIL			FIBERITE RTP		
			CF-1004 20%	CF-1006 30%	CF-1008 40%	G-30/20 20% ^a	G-30/30 30%	G-31/35 35% High Impact	G-35135 35%	J-30/20 20% ^b	J-30/30 30%	A-1000 10%	A-2000 20%	A-3000 30%	403 20%	405 30%	407 40%
Specific Gravity	D792	1.08	1.20	1.28	1.38	1.20	1.29	1.32	1.34	1.20	1.29	1.12	1.20	1.29	1.20	1.28	1.38
Specific Volume, in. ³ /lb		25.6	23.1	21.6	20.1	-	-	-	-	-	-	-	-	-	-	-	-
Water Absorption, %	D570	-	0.07	0.05	0.05	0.1	0.09	0.06	0.06	0.1	0.1	-	-	-	0.07	0.06	0.05
24 h equil. cont. immersion		-	0.14	0.10	0.10	0.3	0.3	0.3	0.3	0.3	0.3	-	-	-	-	-	-
Mold Shrinkage, in./in.	D955																
1/8 in. ave. section		0.002	0.0010	0.0005	0.0005	0.001	0.001	0.001	0.001	0.001	0.001	-	-	-	0.001	0.001	0.0005
1/4 in. ave. section		0.006	0.0020	0.0010	0.0010	0.002	0.002	0.002	0.002	0.002	0.002	-	-	-	0.002	0.001	0.001
Tensile Strength, psi	D638																
73° F		7,000	11,500	13,500	15,000	13,000	14,000	14,500	15,000	10,000	10,500	9,800	10,600	12,500	11,000	12,000	14,000
120° F		-	11,000	12,000	12,500	-	-	-	-	-	-	-	-	-	-	-	-
140° F		-	9,500	9,700	10,000	-	13,000 ^c	14,000 ^c	-	-	-	-	-	-	-	-	-
Tensile Elongation, %	D638	2	2-3	2-3	2-3	-	-	-	-	-	-	3	2	2.0	1.0	1.0	1.0
Tensile Modulus, psi	D638																
73° F		450,000	1,050,000	1,300,000	1,650,000	1,200,000	1,300,000	1,300,000	1,900,000	900,000	1,200,000	-	-	-	1,200,000	1,300,000	2,000,000
120° F		-	1,000,000	1,250,000	1,600,000	-	-	-	-	-	-	-	-	-	-	-	-
140° F		-	950,000	1,200,000	1,550,000	-	1,100,000 ^c	1,000,000 ^c	-	-	-	-	-	-	-	-	-
Flexural Strength, psi	D790	-	15,000	16,200	17,500	16,000	17,000	17,000	18,500	14,000	14,000	-	-	-	16,500	16,800	19,000
Flexural Modulus, psi	D790	-	950,000	1,200,000	1,500,000	1,000,000	1,200,000	1,200,000	1,300,000	950,000	1,200,000	800,000	920,000	1,200,000	1,100,000	1,200,000	1,600,000
Compressive Strength, psi	D695	-	16,700	17,300	17,800	16,000	19,000	16,000	18,000	-	-	-	-	-	-	-	-
Izod Impact Strength, ft•lb/in.	0256																
notched 1/4 in. x 1/2 in. bar		0.25 ^d	0.9	1.0	1.2	2.1	2.2	4.0	2.2	0.9	0.9	0.8	1.0	1.0	1.0	1.1	1.1
unnotched 1/4 in. x 1/2 in. ba		-	2-3	2-3	2-3	-	-	-	-	-	-	-	-	-	2.0	2.1	2.1
Rockwell Hardness	D785	M70	M90	M92	M93	M85-95	M90-100	M85-95	M90-100	M85-95	M85-95	-	-	-	R119	R121	R121
Shear Strength, psi	0732	-	-	-	-	9,000	9,000	7,500	9,000	7,000	7,000	-	-	-	-	-	-
Taber Abrasion, CS-17 wheel	D1044																
1000-g load, mg/1000 cycles		-	-	-	-	280	164	300	-	-	-	-	-	-	-	-	-

^a G Series 1/8 in. dia. x 1/2 in. long glass fiber

^b J Series 1/8 in. dia. x 1/8 in. or 1/4 in. long glass fiber

^c at 170° F

^d 1/8 in. x 1/2 in. bar

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TABLE 3-98. THERMAL PROPERTIES OF POLYSTYRENE

Property	Glass Content	ASTM Test Method	General Purpose Flame Retardant Nonreinforced	THERMOCOMP			STYRAFIL						THERMOFIL			FIBERITE RTP		
				CF-1004 20%	CF-1006 30%	CF-1008 40%	G-30/20 20%	G-30/30 30%	G-31/35 35%	G-35/35 35%	J-30/20 20%	J-30/30 30%	A-1000 10%	A-2000 20%	A-3000 30%	403 20%	405 30%	407 40%
Deformation Under Load 4000 psi, 122° F, 24 h, %		D621	—	0.7	0.4	0.2	0.4	0.3	0.7	0.2	0.6	0.4	—	—	—	—	—	—
Heat Distortion Temperature, °F 66 psi 264 psi		D648	195	220	230	235	215	220	195	220	215	215	—	—	—	220	225	230
			—	200	215	220	225	230	205	230	220	210	205	210	210	200	210	210
Thermal Conductivity, Btu/h•ft ² •°F/in.		Cenco	0.07–0.096"	1.8	2.0	2.2	—	0.117 ^b	0.107 ^b	—	—	—	—	—	—	1.7	2.1	2.2
Coefficient of Linear Thermal Expansion, (in./in. • °F) × 10 ⁻⁵		D696	6.0–8.0	2.2	1.9	1.6	2.3	1.8	2.5	1.8	2.2	1.7	—	—	—	2.2	2.0	1.7
Specific Heat, Btu/lb • °F		C351	0.32	0.28	0.26	0.24	—	0.256	0.237	—	—	—	—	—	—	—	—	—
Melting Point, °F		D789	—	242 ^c	242"	242"	232–242	232–242	214–224	235–245	232–242	232–242	—	—	—	—	—	—
Flammability, in./min		D635	—	1.0	0.9	0.8	—	—	—	—	—	—	1.2	1.8	2.2	B	B	B

^aASTM C177

^bThermal conductivity is measured by Cenco-Fitch Apparatus.

^cFisher-Johns

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TABLE 3-99. ELECTRICAL PROPERTIES OF POLYSTYRENE

Property	ASTM Test Method	STYRAFIL				THERMOFIL			FIBERITE RTP		
		Nonreinforced	G-30/20 20%	G-30/30 30%	G-30/35 35%	A-1000 10%	A-2000 20%	A-3000 30%	403 20%	405 30%	407 40%
Dielectric Strength, V/mil short time step by step	D149	500-700	412	400	420	420	420	420	425	450	450
		400-600	370	350	-	-	-	-	-	-	-
Volume Resistivity, ohm•cm	D257	> 10 ¹⁶	10 ¹⁶	10 ¹⁶	-	-	-	10 ¹⁶	10 ¹⁶	10 ¹⁶	
Dielectric Constant, dimensionless 60 Hz 10 ³ Hz 10 ⁶ Hz	D150	2.45-3.1	2.8	3.0	3.5	-	-	-	-	-	-
		2.40-2.65	2.8	3.0	3.5	-	-	-	-	-	-
		2.40-2.7	2.0	3.0	3.5	-	-	-	3.0	3.2	3.5
Dissipation Factor, dimensionless 60 Hz 10 ³ Hz 10 ⁶ Hz	D150	0.0001-0.0006	0.0005	0.001	0.005	-	-	-	-	-	-
		0.0001-0.0003	0.001	0.001	0.004	-	-	-	-	-	-
		0.0001-0.0004	0.0005	0.002	0.001	-	-	-	0.001	0.002	0.003
Arc Resistance, tungsten electrodes, s	D495	60-140	40	60	40	-	-	-	60	50	40

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TABLE 3-100. PHYSICAL AND MECHANICAL PROPERTIES OF POLYSULFONES

Property	ASTM Test Method	Nonreinforced Polysulfone P-1700	THERMOCOMP			SULFIL					THERMOFIL			FIBERITE RTP		
			GF-1004 20%	GF-1006 30%	GF-1008 40%	G-1500/10 10%	G-1500/20 20%	J-1500/10 10%	J-1500/20 20%	J-1500/30 30%	s-2000 20%	S-3000 30%	S-4000 40%	903 20%	905 30%	907 40%
Specific Gravity, 73° F	D792	1.24	1.38	1.45	1.55	1.31	1.38	1.31	1.38	1.46	1.38	1.47	1.55	1.38	1.46	1.56
Specific Volume, in. ³ /lb	—	22.40	20.1	19.0	17.9	—	—	—	—	—	—	—	—	—	—	—
Water Absorption, %	D570															
24 h, 73° F		0.20	0.20	0.20	0.18	0.2	0.2	0.3	0.3	0.3	—	—	—	0.25	0.23	0.16
equil. cont. immersion, 73° F		0.60	0.60	0.58	0.58	—	0.6	—	—	—	—	—	—	—	—	—
Mold Shrinkage, in./in.	D955	0.007–0.008	0.003–0.004	0.002–0.003	0.0015–0.002	0.004	0.002	0.004	0.002	0.002	—	—	—	0.002–0.003	0.001–0.002	0.001–0.002
Tensile Strength, psi	D638															
–40° F		12,200	19,000	22,000	24,000	—	—	—	—	—	—	—	—	—	—	—
73° F		10,200	15,000	18,000	20,000	15,500	17,500	11,000	14,000	14,500	14,000	16,000	19,500	15,000	17,000	19,000
210° F		7,500	10,000	13,000	16,000	—	—	—	—	—	—	—	—	—	—	—
300° F		5,800	7,000	9,500	12,000	—	—	—	—	—	—	—	—	—	—	—
Elongation, 73° F, %	D638	50–100	3.0	3.0	2.0	2.5	2.0	2.5	2.0	1.5	3.0	2.5	—	2.8	2.1	1.7
Flexural Strength, psi	D790															
–40° F		—	25,000	27,000	32,000	—	—	—	20,000	20,000	—	—	—	—	—	—
73° F		15,400	21,000	24,000	27,000	20,000	23,500	19,000	—	—	—	—	—	20,000	23,000	25,000
210° F		12,300	17,000	19,000	23,000	—	—	—	—	—	—	—	—	—	—	—
300° F		10,000	13,000	15,500	16,800	—	—	—	—	—	—	—	—	—	—	—
Flexural Modulus, psi	D790															
73° F		390,000	850,000	1,200,000	1,600,000	650,000	950,000	650,000	900,000	1,050,000	850,000	900,000	1,300,000	700,000	1,000,000	1,200,000
210° F		365,000	780,000	1,125,000	1,500,000	—	—	—	—	—	—	—	—	—	—	—
300° F		315,000	740,000	1,000,000	1,400,000	—	—	—	—	—	—	—	—	—	—	—
Compressive Strength, psi	D695	13,900	21,000	24,000	25,500	17,000	21,000	15,000	18,000	19,000	—	—	—	19,000	22,000	24,000
Shear Strength, psi	D732	9,000	9,000	9,500	10,000	8,500	9,500	8,000	8,500	9,000	—	—	—	—	—	—
Deformation Under Load, %	D621															
122° F, 2000 psi		0.10	0.08	0.07	0.05	—	—	—	0.04	0.04	—	—	—	—	—	—
122° F, 4000 psi		0.20	0.12	0.10	0.06	0.08	0.08	0.06	—	—	—	—	—	—	—	—
Izod Impact Notched, 1/4 in. bar, ft•lb/in.	D256															
–40° F		1.2	1.2	1.6	2.0	—	29	—	—	—	—	—	—	1.1	1.3	1.6
73° F		1.2	1.3	1.8	2.0	1.3	2.0	0.8	1.0	1.1	1.1	1.3	1.3	9.0	10.0	11.0
Izod Impact Unnotched, 1/4 in. bar, ft•lb/in.	D256	>60	12	14	16	—	—	—	—	—	—	—	—	—	—	—
Tensile Impact, "S" Type, ft•lb/in. ²	D1822	250	48	63	82	—	—	—	—	—	—	—	—	—	—	—
Rockwell Hardness	D785	M69, R 120	M92, L107	M92, L108	M92, L109	M80–90	M85–95	M80–90	M85–95	M90–100	—	—	—	R 123	R123	R123
Tabor Abrasion, CS-17 wheel, 1000 g-load, mg/1000 cycles	D1044	20	35–40	35–40	35–40	—	—	—	—	—	—	—	—	—	—	—
Fatigue Endurance Limit, at 2 × 10 ⁶ cycles, psi	D671	1250	—	5400	—	—	—	—	—	—	—	—	—	—	—	—
Tensile Modulus, psi	D638	—	—	—	—	750,000	1,100,000	600,000	950,000	1,350,000	—	—	—	880,000	1,200,000	1,700,000

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TABLE 3-101. THERMAL PROPERTIES OF POLYSULFONE

Property	Glass Content ASTM Test Method	THERMO COMP				SULFIL					THERMOFIL			FIBERITE RTP		
		P-1700 Non-reinforced	GF-1004 20%	GF-1006 30%	GF-1008 40%	G-1500/10 10%	G-1500/20 20%	J-1500/10 10%	J-1500/20 20%	J-1500/30 30%	S-2000 20%	S-3000 30%	S-4000 40%	903 20%	905 30%	907 40%
Heat Deflection, Temperature, °F 264 psi 66 psi	D648	345	360	365	370	340	345	345	345	350	355	360	365	360	362	365
		358	370	375	380	350	360	355	360	360	—	—	—	365	370	375
Thermal Conductivity, Btu/h•ft ² •°F/in.	C177	1.8	2.0	2.2	2.5	—	—	—	—	—	—	—	—	2.1	2.2	2.6
Coefficient of Linear Thermal Expansion, (in./in.•°F) X 10 ⁻⁵	0696	3.1	1.7	1.4	1.2	2.0	1.7	2.0	1.7	1.4	—	—	—	1.7	1.4	1.3
Flammability	UL Subj. 94 0635	94v1	94V1	94v1	94V1	—	—	—	—	—	—	—	—	VE 1	VEO	VEO
		—	—	—	—	—	—	—	—	—	—	SE	SE	SE	SE	SE

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TABLE 3-102. ELECTRICAL PROPERTIES OF POLYSULFONES

Glass Content Property	ASTM Test Method	THERMOCOMP GF-1006 30% FIBER GLASS FORTIFIED POLYSULFONE				THERMOFIL			FIBERITE RTP		
		Non- reinforced 73" F	50% RH 73" F	210" F	300" F	S-2000/ 20%, 73" F	S-30001 30%, 73" F	S-4000/ 40%, 73" F	903 20% 73" F	905 30% 73" F	907 40% 73" F
Dielectric Strength, short time, V/mil	D149	425	480	550	—	460	485	485	430	430	430
Dielectric Constant, dimensionless	D150										
60 Hz		3.07–3.14	3.55	3.41	3.27	—	—	—	—	—	—
10 ³ Hz		3.06–3.13	3.55	3.41	3.30	—	—	—	—	—	—
10 ⁶ Hz		3.03–3.10	3.49	3.21	2.95	—	—	—	3.6	3.65	3.75
Dissipation Factor, dimensionless	D150										
60 Hz		0.0008	0.0019	0.0018	0.0010	—	—	—	—	—	—
10 ³ Hz		0.0010	0.0015	0.0019	0.0025	—	—	—	—	—	—
10 ⁶ Hz		0.0034	0.0049	0.0050	0.0053	—	—	—	0.005	0.005	0.005
Arc Resistance, s	D495	75–122	115	—	—	—	—	—	100	100	120
Volume Resistivity, ohmcm	D257	5.0 × 10 ¹⁶	10 ¹⁷	5 × 10 ¹⁵	10 ¹⁵	—	—	—	10 ¹⁵	10 ¹⁵	10 ¹⁵

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TABLE 3-103. PHYSICAL AND MECHANICAL PROPERTIES OF POLYURETHANE

Property	Glass Content ASTM Test Method	THERMOCOMP				URAFIL				FIBERITE RTP		
		No reinforced Polyurethane Elastomer	TF-1004 20%	TF-1006 30%	TF-1008 40%	G-100/20 20%	G-100/30 30%	G-100/40 40%	J-100/20 20%	1203 20%	1205 30%	1207 40%
Specific Gravity	0792	1.05–1.25	1.37	1.46	1.55	1.36	1.44	1.53	1.36	1.37	1.45	1.54
Specific Volume, in. ³ /lb	0792	26.5–22.0	20.2	19.0	17.9	–	–	–	–	–	–	–
Water Absorption, % 24 h to saturation	0570	0.7–0.9 –	0.30 0.85	0.25 0.75	0.20 0.65	0.55 1.5	0.52 1.4	0.49 1.3	0.55 1.5	0.15 –	0.15 –	0.15 –
Mold Shrinkage, 1/8 in. ave. section, in./in	D955	0.001–0.03	0.0050	0.0040	0.0030	0.007 ^a	0.006 ^a	0.004 ^a	0.007 ^a	0.004	0.003	0.002
Tensile Strength, psi	0638	4,500–8,400	6,800	8,200	9,600	5,000 ^b	7,000 ^b	10,000 ^b	6,000	14,000	17,000	19,000
Tensile Elongation, %	0638	100–650	30	25	20	3.0 ^b	2.5 ^b	2.0 ^b	35	3.3	3.5	3.8
Flexural Strength, psi	0790	700–9,000	4,300	5,600	6,900	5,000	6,000	7,000	5,500	19,000	23,000	25,000
Flexural Modulus, psi	0790	100,000	125,000	190,000	260,000	150,000	250,000	360,000	150,000	620,000	800,000	1,000,000
Shear Strength, psi	0732	–	4,300	4,800	5,400	4,500	–	6,000	–	–	–	–
Izod Impact Strength, ft•lb/in. notched 1/4 in. unnotched 1/4 in.	0256	does not break ^d –	10.0 28–29	9.5 28–29	9.0 27–28	10.0 –	10.0 –	10.0 –	9.0 –	1.5 10.0	2.0 15.0	3.0 24.0
Shore Hardness	D2240	65A–80D	D60	D65	D70	R45–55 ^c	R55–65'	R65–75''	R45–55'	R115	R117	R119
Compressive Strength, psi	0695	–	–	–	2,500	–	7,000	–	–	10,000	12,000	13,000

^a Data from laboratory specimens. For mold design a figure of 20% to 25% of mold shrinkage of unreinforced material is recommended.

^b At yieldpoint

^c Rockwell Hardness

^d 1/2 in. x 1/2 in.

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TABLE 3-104. THERMAL PROPERTIES OF POLYURETHANE

Property \ Glass Content	ASTM Test Method	THERMOCOMP				URAFIL				FIBERITE RTP		
		Nonreinforced Polyurethane Elastomer	TF-1004 20%	TF-1006 30%	TF-1008 40%	G-100/20 20%	G-100/30 30%	G-100/40 40%	J-100/20 20%	1203 20%	1205 30%	1207 40%
Heat Distortion Temperature, °F 66 psi 264 psi	D648	—	310	315	320	160	160	165	150	260	270	280
		131	165	170	175	140	145	155	130	170	185	200
Thermal Conductivity, Btu/h•ft ² •°F/in.	C177	—	2.6	2.9	3.1					2.5	2.8	3.0
Coefficient of Linear Thermal Expansion, (in./in.•°F) x 10 ⁻⁵	D696	7.7	4.5	2.5	1.4	1.5	1.3	1.1	—	4.0	2.4	1.5
Flammability		—	94HB	94HB	94HB	—	—	—	—	HB	HB	HB
Deformation under load at 1000 psi and 122° F, %	D621	—	—	—	—	0.6	0.5	0.4	0.6	—	—	—

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TABLE 3-105. ELECTRICAL PROPERTIES OF POLYURETHANE

Property	Glass Content	ASTM Test Method	FIBERITE RTP			
			Nonre-inforced	1203 20%	1205 30%	1207 40%
Dielectric Strength, short time, V/m		D 149	500	450	450	450
Dielectric Constant at 10^6 Hz, dimensionless		D150	5.1	4.8	4.5	4.2
Dissipation Factor at 10^6 Hz, dimensionless		D150	0.1	0.012	0.014	0.017
Volume Resistivity, ohmcm		D257	10^{12}	10^{11}	10^9	10^{11}
Arc Resistance, s		D495	122	90	90	90

TABLE 3-106. PHYSICAL AND MECHANICAL PROPERTIES OF PVC

Property	Glass Content	ASTM Test Method	THERMOCOMP		THERMOFIL
			Nonreinforced Rigid	VF-1003 15%	v-2000 20%
Specific Gravity		D792	1.30-1.58	1.54	1.58
Specific Volume, in. ³ /lb		D792	20.5-19.1	18.0	—
Water Absorption, %		D570			
24 h			0.4	0.01	—
equil. cont. immersion			—	0.08	—
Mold Shrinkage, 1/8 in. ave. section, in./in.		D955	0.001-0.005	0.001	—
Tensile Strength, psi		D638			
73°F			6,000-7,500	13,000	14,000
120°F			—	9,500	—
140°F			—	7,000	—
Tensile Elongation, %		D638	40-80	2-3	10
Tensile Modulus, psi		D638			
73°F			—	1,000,000	—
120°F			—	900,000	—
140°F			—	750,000	—
Flexural Strength, psi		D790	10,000-16,000	18,000	—
Flexural Modulus, psi		D790	300,000-500,000	850,000	—
Compressive Strength, psi		D695	8,000-13,000	12,000	—
Shear Strength, psi		D732	—	7,000	—
Izod Impact Strength, ft•lb/in.		D256			
notched 1/4 in. x 1/2 in. bar			0.4-20.0	1.2	1.5 ^a
unnotched 1/4 in. x 1/2 in. bar			—	6.5	—
Rockwell Hardness		D785	D65-85	M78, R115	—

^a1/8 in. bar

TABLE 3-107. THERMAL PROPERTIES OF PVC⁴⁶

Property	Glass Content	ASTM Test Method	Non-reinforced	THERMOCOMP	THERMOFIL		
				VF-1003 15%	v-2000 20%		
Heat Distribution Temperature, °F		D648					
				66 psi	135-180	165	—
				264 psi	140-170	155	180
Thermal Conductivity, Btu/h • ft ² • °F/in.		Cenco	3.5-5.0	1.6	—		
Coefficient of Linear Thermal Expansion, in./in. • °F		D696	—	1.7 x 10 ⁻⁵	—		
Flammability		UL Subj. 94	—	94V0	—		
Flammability, in./min		D635	0.04-0.4	—	SE		

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TABLE 3-108. PHYSICAL AND MECHANICAL PROPERTIES OF SAN

Glass Content	ASTM Test Method	THERMOCOMP					ACRYLAFIL				THERMOFIL				FIBERITE RTP		
		SAN Non-reinforced	BF-1004 20%	BF-1006 30%	BF-1007 35%	BF-1008 40%	G-40/20 20%	G-40/35 35%	J-40/20 20%	J-40/35 35%	B-2000 20%	B-3000 30%	B-3500 35%	BSE-2000 20%	503 20%	505 30%	507 40%
Specific Gravity	D792	1.075–1.100	1.22	1.31	1.35	1.40	1.22	1.35	1.22	1.35	1.22	1.31	1.35	1.3	1.22	1.31	1.40
Specific Volume, in. ³ /lb	D792	25.8–25.2	22.7	21.2	20.5	19.8	–	–	–	–	–	–	–	–	–	–	–
Water Absorption, % 24 h equil. cont. immersion	D570	0.20–0.30	0.15 0.36	0.10 0.32	0.09 0.30	0.08 0.28	0.22 0.7	0.15 0.5	0.22 0.7	0.20 0.5	–	–	–	–	0.2	0.15	0.1
Mold Shrinkage, in./in. 1/8 in. ave. section 1/4 in. ave. section	D955	0.002 0.007	0.0010 0.0020	0.0005 0.0010	0.0005 0.0010	0.0005 0.0010	0.001 0.002	0.001 0.002	0.001 0.002	0.001 0.002	–	–	–	–	0.001 0.002	0.001 0.001	0.001 0.001
Tensile Strength, psi 73° F 120° F 140° F	D638	9,000–12,000	15,800 15,000 12,500	17,400 16,000 13,000	18,000 16,100 13,200	18,600 16,300 13,500	13,000	18,000 16,000 ^a	13,000	17,000	15,200	17,000	17,500	12,000	18,000	19,000	20,000
Tensile Elongation, %	D638	1.5–3.7	2–3	2–3	2–3	2–3	1.2	1.4	1.5	1.2	2.0	2	2	1.5	1.8	1.6	1.4
Tensile Modulus, psi 73° F 120° F 140° F	D638	00,000–560,000	1,150,000 1,100,000 1,050,000	1,600,000 1,550,000 1,500,000	1,750,000 1,700,000 1,650,000	1,950,000 1,900,000 1,850,000	1,200,000	1,800,000	1,000,000	1,700,000	–	–	–	–	1,200,000	1,600,000	2,000,000
Flexural Strength, psi	D790	10,500–20,000	19,800	22,000	22,700	23,200	20,000	22,000	18,000	19,000	–	–	–	–	20,000	22,000	24,000
Flexural Modulus, psi	0790	8,000-1,000,000	1,100,000	1,500,000	1,650,000	1,850,000	1,100,000	1,400,000	1,000,000	1,300,000	1,100,000	1,300,000	1,500,000	1,200,000	1,000,000	1,400,000	1,800,000
Compressive Strength, psi	0695	–	19,400	21,000	22,000	23,200	17,000	23,000	17,000	21,000	–	–	–	–	19,000	21,000	22,000
Shear Strength, psi	0732	–	9,000	9,400	9,600	9,800	10,000	11,000	9,000	9,500	–	–	–	–	–	–	–
Izod Impact Strength, ft•lb/in. notched 1/4 in. bar unnotched 1/4 in. bar	D256	0.35–0.50	1.0 3–4	1.0 3–4	1.1 3–4	1.1 3–4	2.5	3.0	0.8	0.8	1.0 ^b	1.0 ^b	1.2 ^b	0.8 ^b	1.0	1.1	1.1
Rockwell Hardness	D785	M80–90	M92, R 122	M94, R 123	M96, R 123	M97, R 123	M90–100	M90–100	M85–95	M90–100	–	–	–	–	R122	R123	R123

^a at 170° F

^b 1/8 in. bar

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TABLE 3-109. THERMAL PROPERTIES OF SAN

Property	Glass Content	ASTM Test Method	THERMOCOMP					ACRYLAFIL				THERMOFIL				FIBERITE RTP		
			SAN Nonreinforced	BF-1004 20%	BF-1006 30%	BF-1007 35%	BF-1008 40%	G-40/20 20%	G-40/35 35%	J-40/20 20%	J-40/35 35%	B-2000 20%	B-3000 30%	B-3500 35%	BSE-2000 20%	503 20%	505 30%	507 40%
Heat Distortion Temperature, °F 66 psi 264 psi		D648	190–220	220	230	230	235	220	220	215	216	–	–	–	–	220	225	230
			–	205	215	215	220	230	230	225	226	210	215	220	210	210	212	217
Thermal Conductivity, Btu/h•ft ² •°F/in.		Cenco	0.84 ^a	1.8	2.0	2.1	2.2	–	–	–	–	–	–	–	1.9	2.0	2.1	
Coefficient of Linear Thermal Expansion, (in./in.•°F) x 10 ⁻⁵		D696	3.6	2.1	1.8	1.6	1.5	–	1.6	2.3	1.8	–	–	–	2.2	1.9	1.55	
Specific Heat, Btu/lb•°F		C351	0.31	0.21	0.25	0.28	0.28	–	–	–	–	–	–	–	–	–	–	
Flammability		UL Subj. 94	–	94HB	94HB	94HB	94HB	–	–	–	–	–	–	–	HB	HB	HB	
Flammability, in./min		D635	–	–	–	–	–	–	–	–	–	–	–	1.3	2.1	2.3	SE	

^a ASTM 177

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TABLE 3-110. ELECTRICAL PROPERTIES OF SAN

Property	Glass Content	ASTM Test Method	ACRYLAFIL		THERMOFIL				FIBERITE RTP		
			Nonreinforced	G-40/35 35%	B-2000 20%	B-3000 30%	B-3500 35%	BSE-2000 20%	503 20%	505 30%	507 40%
Dielectric Strength, V/mil short time step by step	D149		400–800	500	425	430	430	400	500	500	500
			300–600	400	–	–	–	–	–	–	–
Volume Resistivity, ohmcm		D257	10 ¹⁶	10 ¹⁶	–	–	–	–	10 ¹⁶	10 ¹⁶	10 ¹⁶
Surface Resistivity, ohm		D257	–	10 ¹⁷	–	–	–	–	–	–	–
Dielectric Constant, dimensionless	D150		2.6–3.4	3.6	–	–	–	–	–	–	–
			10 ³ Hz	2.6–3.3	3.5	–	–	–	–	–	–
			10 ⁶ Hz	2.6–3.1	3.4	–	–	–	–	3.5	3.6
Dissipation Factor, dimensionless	D150		0.006–0.008	0.005	–	–	–	–	–	–	–
			10 ³ Hz	0.007–0.012	0.006	–	–	–	–	–	–
			10 ⁶ Hz	0.007–0.010	0.009	–	–	–	–	0.008	0.008
Arc Resistance, tungsten electrodes, s		0495	100–150	65	–	–	–	–	70	60	60

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CHAPTER 4

PROCESSING GLASS-REINFORCED THERMOPLASTICS

Processing techniques— injection molding, rotational molding, and solid-phase forming—are described in detail. Machines, controls, automation, auxiliary equipment and tooling, material handling equipment, and safety precautions are treated in the discussion. Advantages and disadvantages (limitations) of the fabrication processes are presented. Problems encountered in fabrication and suggested solutions are presented. Resin systems and forms related to various fabrication methods are discussed. Finally, the techniques for decorating GRTP's are discussed briefly.

4-1 INTRODUCTION

Of the many thermoplastic processing techniques, three major processes— injection molding, rotational molding, and solid-phase forming—generally are used to fabricate products from glass-reinforced thermoplastic materials (GRTP). Of these processes, injection molding constitutes the largest effort. The basic fabrication characteristics of GRTP are dependent on the polymer or matrix system. However, the addition of glass fibers to the polymer changes some of the processing parameters. As previously stated, the improved properties of the composites are dependent on a critical minimum fiber length. Therefore, processing conditions have been established to yield the strongest parts possible by avoiding fiber length attrition below the critical length.

4-2 INJECTION MOLDING

4-2.1 DEFINITION

In injection molding, the fiberglass and resin system are introduced into a heating chamber where the mixture softens and is injected under pressure into a matched-metal mold cavity. The material then cools and solidifies into its intended shape. It is then ejected from the mold and trimmed of runners and flash if necessary. The mold may consist of a single cavity or a number of similar or dissimilar cavities, each connected to flow channels (runners) which direct the melted plastic to the individual cavities.

The resin-glass system can be introduced in three ways:

1. A compounded resin pellet usually 1/8 in. in diameter by 1/8 in. or more in length containing between 10% and 50% glass reinforcement by weight. The pellet also contains appropriate additives such as stabilizers, pigments, and lubri-

cants. Such formulations can be selected for optimum properties in specific applications.

2. Concentrated resin pellets containing 50-80% glass reinforcement by weight. These pellets are mixed or diluted to appropriate reinforcement levels with their respective nonreinforced resin pellets.

3. Direct blending of chopped glass strand and resin powder in the injection molding machine.

Injection molding is considered one of the most economical methods of high volume mass production. The molded part is usually a finished item requiring minimum or no secondary operations such as flash removal, drilling, threading, and coring. This process also permits each change of materials, colors, and molds; broad part design flexibility; dimensionally precisioned parts; excellent cycle-to-cycle reproducibility; molded-in inserts; and low scrap loss (as a result of hot runners or reground sprues and runners). Molding cycles are relatively fast and the process lends itself to varying degrees of automation.

4-2.2 INJECTION MOLDING MACHINES

The injection molding machine consists of the following components:

1. Material feeding and metering systems
2. Heating and plasticating systems (heating chambers, heaters, torpedoes)
3. Melt delivery systems (single and double stage plungers, screw and plunger combinations, reciprocating screws, nonreturn valves)
4. Nozzles (plain, pinpoint, mixing, valved)
5. Press operating systems (opening, closing, and clamping systems; hydraulic and electrical operating systems and controls).

Injection machines are classified generally into three types— reciprocating screw, ram or plunger, and two-stage or preplasticizers— described in the paragraphs that follow. Most injection

molding machines are horizontal in which the clamping and injection units operate in the same plane. Vertical platen machines are used primarily for insert molding where automatic hopper-fed insert loaders can be used.

4-2.2.1 Reciprocating Screw Machine

The reciprocating screw machine consists of a barrel or cylinder and a screw which rotates to melt and mix the material and then moves forward to force the melt into the mold (see Fig. 4-1).

Of all the injection molding machines, the in-line reciprocating screw machine is preferred for molding GRTP. This is because it offers improved mixing with more homogeneous melt, good dispersion of glass fibers, and reduced pressure loss through the cylinder. Other advantages are shorter cycle times, superior part appearances, and lower molded-in stresses. Most all new machines today are of the reciprocating screw type.

The cylinder of injection machines, constructed of heavy steel walls designed to support high internal pressures, functions as a heat exchanger. It also acts as a heat sink to hold temperatures constant. The internal surfaces are highly polished to reduce the friction between the mixer, material, and cylinder wall when the material is being forced through the cylinder. Cylinder liners of Xaloy and nitrided steel, and chrome-plated surfaces are used to resist the abrasiveness and corrosiveness of the plastic melt.

Cylinders are usually heated by electrical resistance. Replaceable band-type heaters are fitted at intervals about the periphery of the cylinder, forming different heat zones. Heat requirements along the cylinder length vary and depend upon the material being processed (see Table 4-1). Heat is transferred to the material through the cylinder walls. However, to prevent possible material hang-up, the area of the cylinder which contacts the hopper feed sleeve usually is water cooled to avoid premature softening of the material as it flows from the hopper.

The rheological and thermal conductivity properties of the polymer matrix determine the heat necessary to melt the material. Relatively shear-sensitive materials become less viscous as they pass through the nozzle. For example, nylons form low viscous fluids when melted while polyethylene can undergo considerable mechanical working, producing heat necessary for plastication.

At the final filling stage, the melt flow is nearly static and the pressure builds up to pack the mold cavity. In order to prevent overpacking or to iron out surface wrinkles and sinks caused by contraction of the cooling plastic, many machines have a secondary system to increase or decrease the injection pressure.

4-2.2.2 Ram or Plunger Machines

The ram injection machine consists of a cylinder, spreader or torpedo, and plunger which forces the melt into the mold.

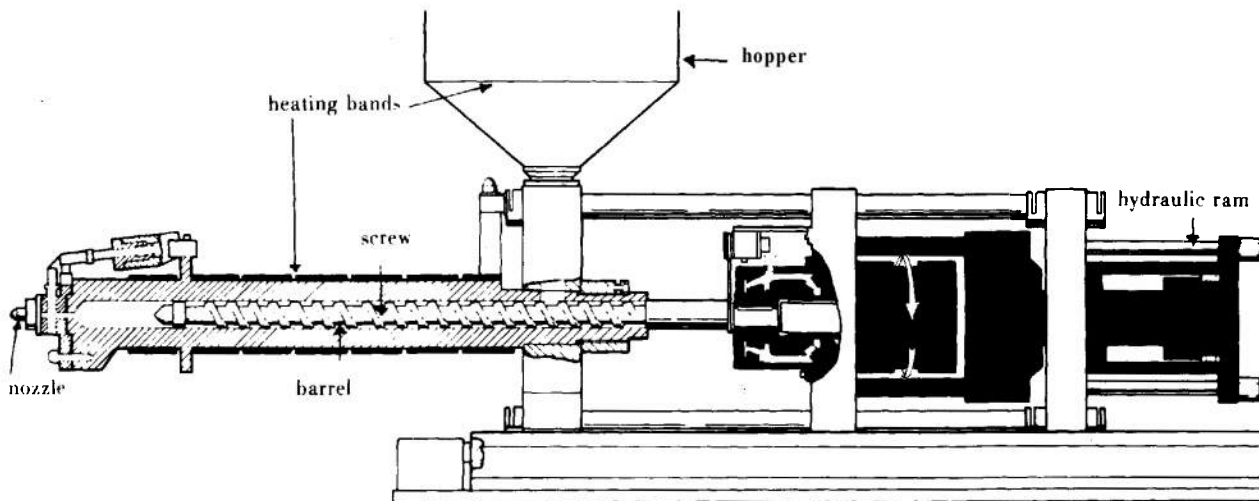


Figure 4-1. Reciprocating Screw Process

TABLE 4-1. SUGGESTED INJECTION MOLDING PROCESSING PARAMETERS

20-30% Glass Resin System	Drying Time and Temperature, °F	Melt Temperature, °F	Cylinder Temp, °F	Stock Temp, °F	Mold Temp, °F	Nozzle Temp, °F	Injection Pressure, psi	Screw Speed, rpm	Back Pressure, psi
Acetal									
Celcon GC25	Not required	380-420'	380'	-	200-250'	420°	14,000-20,000	Minimum	-
Formalafil	Not required	-	350°-410'	380°-420°	180°-250"	-	-	-	-
A8S	2-8 h at 170°-190'	450°-530'	400°-560'	480°	200'	-	-	-	-
Polyamides									
Nylon 6	1 h at 235' 2 h at 220° 5 h at 210° 16 h at 165°	540'	480°-550'	-	200'	-	14,000	-	-
Nylon 6/6	16 h at 165'	520°-580'	500°-575°	-	225'	-	-	-	-
Nylon 6/10	16 h at 165°	540°	480°-550'	-	200°	-	-	-	-
Nylon 6/12	16 h at 165°	540°	480°-550'	-	200°	-	-	-	-
Nylon 11	-	-	490°-540°	-	-	-	-	-	-
Nylon 12	-	-	450°-535'	-	-	-	-	-	-
Polycarbonate	16 h at 250'	580°-625"	575°-650'	600°	160°-250'	-	-	-	-
Polyethersulfone	Not required, if wet 3 h at 300° or 6 h at 250'.	600°-780'	600°-780'	-	200°	-	20,000	30-60	0-100
Polyethylene									
High Density 5% GR	Not required	410°-470'	Rear 450° front 420°	-	90°-120'	-	10,000-15,000	30-60	-
10% GR	Not required	430°-500'	Rear 470° front 440°	-	90°-120'	-	10,000-15,000	30-60	-
20% GR	Not required	460°-520'	Rear 490° front 460°	-	90°-120°	-	10,000-15,000	30-60	-
30% GR	Not required	480°-550"	Rear 500° front 480°	-	90°-120°	-	10,000-15,000	30-60	-
Polyester									
Polyethylene terephthalate	3.5 h at 302° 4 h at 284° 4.5 h at 266° 5 h at 248° Must be kept at 230°-248° in hopper drier during molding.	-	-	-	122°-158° ^a or 266°-302°	-	11,000-14,000	-	-
Polyethylene terephthalate ^b	8 h at 215° 3 h at 280° Also kept at 200° to 225° in hopper drier during molding.	450°-480'	450°-470°	-	100°-250°	470°	7,800-15,000	25-75	0-50
Polytetramethylene-terephthalate	3-4 h at 248°	572°	540°-560'	-	122°-212° or 176°-212°	-	8,000	30-60	0
Polyethylene-tetrafluoroethylene (ETFE)	Not required	600'	560°-650"	-	100°-350°	-	Minimum	30-60	0-100
Polytetrafluoroethylene propylene	Not required	675'	600°-700°	-	450°	-	-	-	-
Modified Polyphenylene oxide	2-4 h at 225°-250°	570°-580'	520°-570'	-	190°-220°	580°	15,000-20,000	40-80	50-70
Polypropylene	Not required	440°-580'	420°-610'	-	90°	-	700-1,900	-	-
Polysulfone	1 h at 250° 16 h at 200°	670°-750'	625°-750'	-	200°-300°	-	-	-	-
Polyphenylene Sulfide	Not required	600'	550°-650'	-	100°-400°	-	Maximum	30-60	0-100
Polystyrene	4 h at 160°	470°-550'	430°-625°	-	60°-175°	-	-	-	-
Polyurethane	2-3 h at 220°	400°	370°-430°	-	70°-180°	-	Minimum	30-60	0-100
Styrene Acrylonitrile	4 h at 160°	450°-530'	430°-550'	-	160°	-	-	-	-

^a If molded item is to be used above 176° F, it must be heat treated 10 min at 302° F, 12 min at 284° F, 20 min at 266° F, 30 min at 248° F, or 180 min at 230° F.

^b If molded item is to be used above 200° F, it must be heat treated 1-3 h at 400° ± 5° F.

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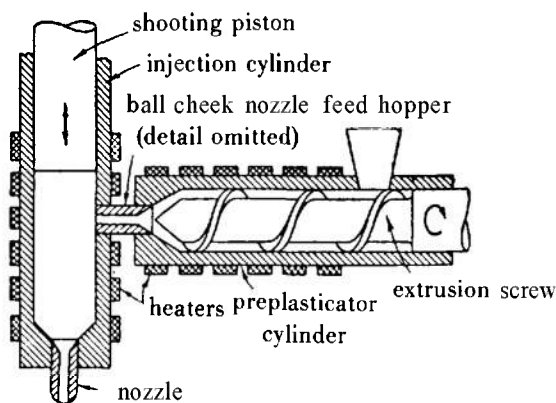
Glass/resin pellets are fed from a hopper into the cylinder in measured amounts (by volume or weight) when the plunger is in the back position. Plastication commences when the plunger travels forward at high pressure and compacts the pellets into the rear of the cylinder. This forces the same weight of melted plastic through the nozzle and into the mold.

The purpose of the spreader or torpedo is to reduce the thickness of the material to facilitate heat transfer. Heated torpedoes are available in some machines to further increase the heat transferred to the material as it passes between the torpedo and cylinder wall. Materials with high thermal conductivities can benefit from heated torpedoes.

G RTP can be molded on ram machines but they are generally not recommended because of their high heat input, poorer glass dispersion, less homogeneous melt, and inability to use direct processing (powder-glass) techniques.

4-2.2.3 Preplasticizers

Preplasticizer machines have been developed to overcome melt degradation and uneven melt heat problems associated with the larger capacity plunger machines. In preplasticating units, plastication is carried out in a separate cylinder which feeds molten material into an injection cylinder.



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Figure 4-2. Screw-Type Preplasticizer²

The plastic melt in the injection cylinder is subjected to just enough pressure to force the plunger back until the correct amount of melt has accumulated in front of the plunger. During the injection stroke, gases escape between the plunger and cylinder wall with a bit of melted plastic which is occasionally collected and discarded.

Two types of preplasticizer machines are shown in Figs. 4-2 and 4-3. The two-stage plunger system shown in Fig. 4-3 is similar to the single plunger system except the melt is forced into a second chamber instead of the mold. The melt is then forced into the mold by the second plunger. The direction of melt flow is controlled by a 3-way rotary valve.

The advantages of this system are:

1. The preplasticating chamber can provide a large volume of plastic melt to the injection chamber at comparatively low pressures.
2. Less pressure is required by the injection plunger to fill the mold since little pressure drop is encountered.
3. The melt is more evenly heated.
4. Larger and stronger components can be molded than with the single-stage plunger.

Another preplasticating design, illustrated in Fig. 4-2, is a fixed screw and ram. The only difference between the ram system and the screw system is a rotating screw used to melt the plastic and extrude it into the injection cylinder. The advantage of the screw system over the two-stage plunger system is that the melt—as a result of the extruding action of the screw—is better mixed with fewer variations in temperature.

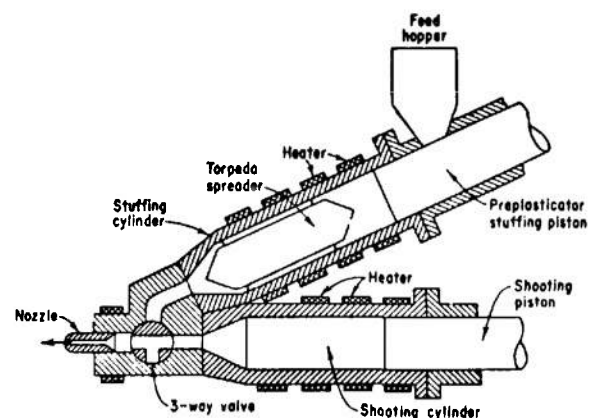


Figure 4-3. Ram-Type Preplasticizer²

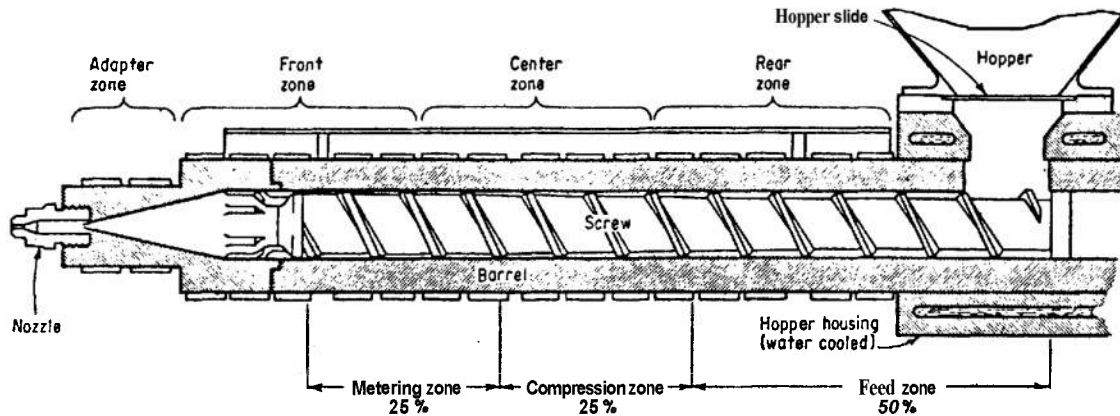


Figure 4.4. Section of In-Line Reciprocating Screw Injection Machine, Showing Screw Zones and Their Percentages of Total Length²

A reciprocating screw is also used instead of the fixed screw. This system has the advantage that it permits continuous plasticating while the injection plunger is filling the mold.

4-2-2.3.1 Screw Design

Figs. 4.4 and 4-5 depict the design characteristics of a reciprocating screw. Screw lengths are divided into three zones—feed, compression, or transition and metering zones—depending on their function and heating requirements. Heat generally is increased from zone to zone. For example, depending on the material system, the temperature is approximately 10-20 deg F higher in the central zone and 30-40 deg F higher in the front zone than in the rear zone.

As the screw rotates, the feed zone conveys the glass-resin material to the beginning of the com-

pression zone. The flight depth of the feed zone is generally constant. In the compression zone, the flight depth is gradually reduced, forcing the plastic to compress. The ratio of flight depths is called the compression ratio. The recommended compression ratio for most GRTP is 2:1. Besides the heat input from the cylinder wall in the compression zone, heat is generated and absorbed by the material from the work involved in shearing the material.

From the compression zone, the melt enters the metering zone. Here the melt temperature is the highest, usually higher than the cylinder barrel surface due to the shearing forces within the plastic mass.

The metering zone conveys the melt through an antibackflow valve and across the nose cone tip to the front of the barrel. The pressure build-up, from the melt in front of the screw, forces the rotating screw back until it trips a limit switch which stops the rotation. The melted plastic is now ready to be injected into the mold by hydraulic pressure applied to the injection ram.

An injection pressure capability of at least 20,000 psi is suggested for glass-reinforced thermoplastics. Screw length to diameter (L/D) ratios of 20:1 are acceptable and favorable for gradual controlled heat up of glass and resin. Melt hot size from 50-80% of machine capacity usually gives excellent results. Small shots in large equipment result in excessive residence times, causing molding difficulties.

Chrome-plated 4140 material is preferred for screw fabrication with stellite-tipped flights as is Xaloy and nitrided steel for cylinder barrel liners.

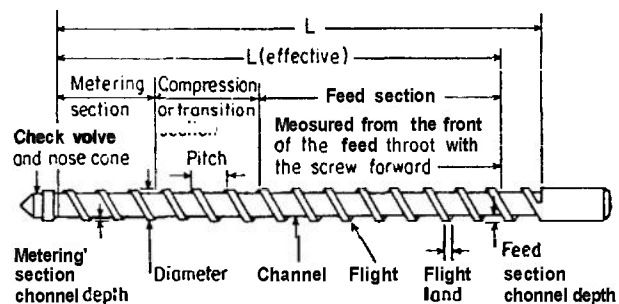


Figure 4.5. Nomenclature for Metering-Type Reciprocating Screw²

Low screw speed, 30-75 rpm, is recommended to avoid excessive glass breakage.

4-2.2.3.2 Back Pressure

The pressure on the plastic melt required to move the screw back can be altered by metering the oil being forced out of the heat end of the hydraulic cylinder. Increasing the back pressure will result in an increase in mechanical shearing, increase the heat generated, and slow down the screw pump-back rate.

High back pressures and high screw speeds tend to reduce the length of the glass fibers in the melt, causing a reduction in the material properties. Also, the increased shearing and heat can degrade heat sensitive materials. Generally, a minimum back pressure of 0-50 psi is recommended for GRTP.

Successful fabrication depends upon a favorable condition of the barrel heat profile, back pressure, and screw rpm for each mold design and material. See Table 4-1 for specific recommendations.

4-2.2.3.3 Controls and Instrumentation

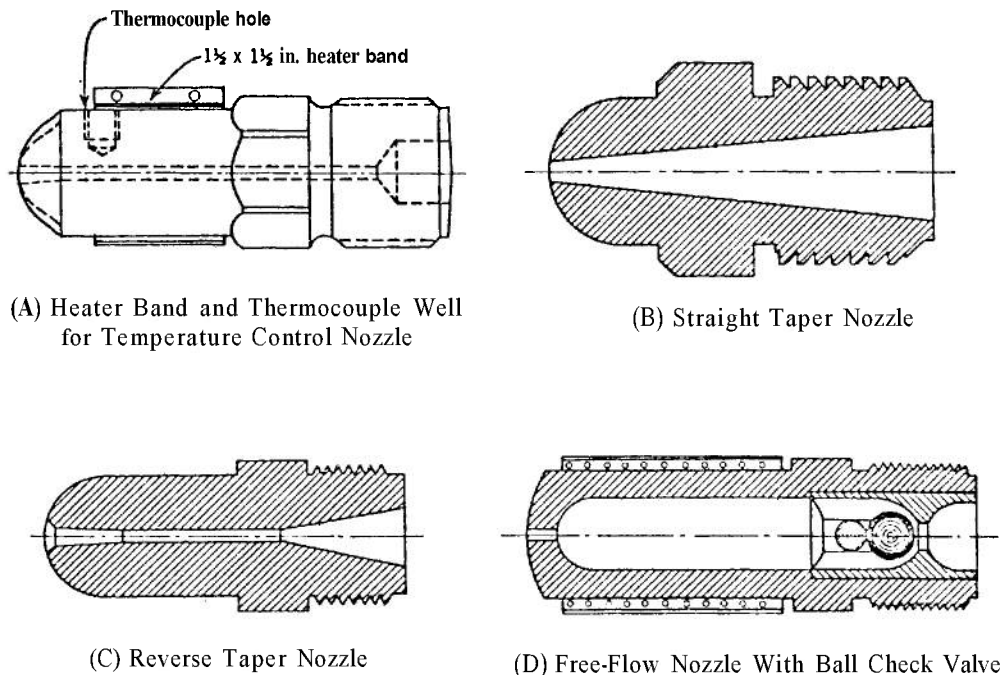
Appropriate controls are required for selecting rotating speed and torque, injection speed, barrel heat zones, and water cooling the rear of the barrel.

4-2.2.3.4 Valves

Two valves are usually used in injection machines. One prevents the back flow of melt along the flights of the screw. The other valve aids in preventing the drooling of plastic from the nozzle when the mold is open.

4-2.2.4 Nozzles

The nozzle of an injection-molding machine is the connection which transfers the plastic melt from the injection cylinder to the mold. It must support very high pressures encountered in injection molding, maintain a good seal at its junction with the mold, act as a heat sink, and not permit the material to ooze or drool under static pres-



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Figure 4-6. Nozzles for Injection Molding³

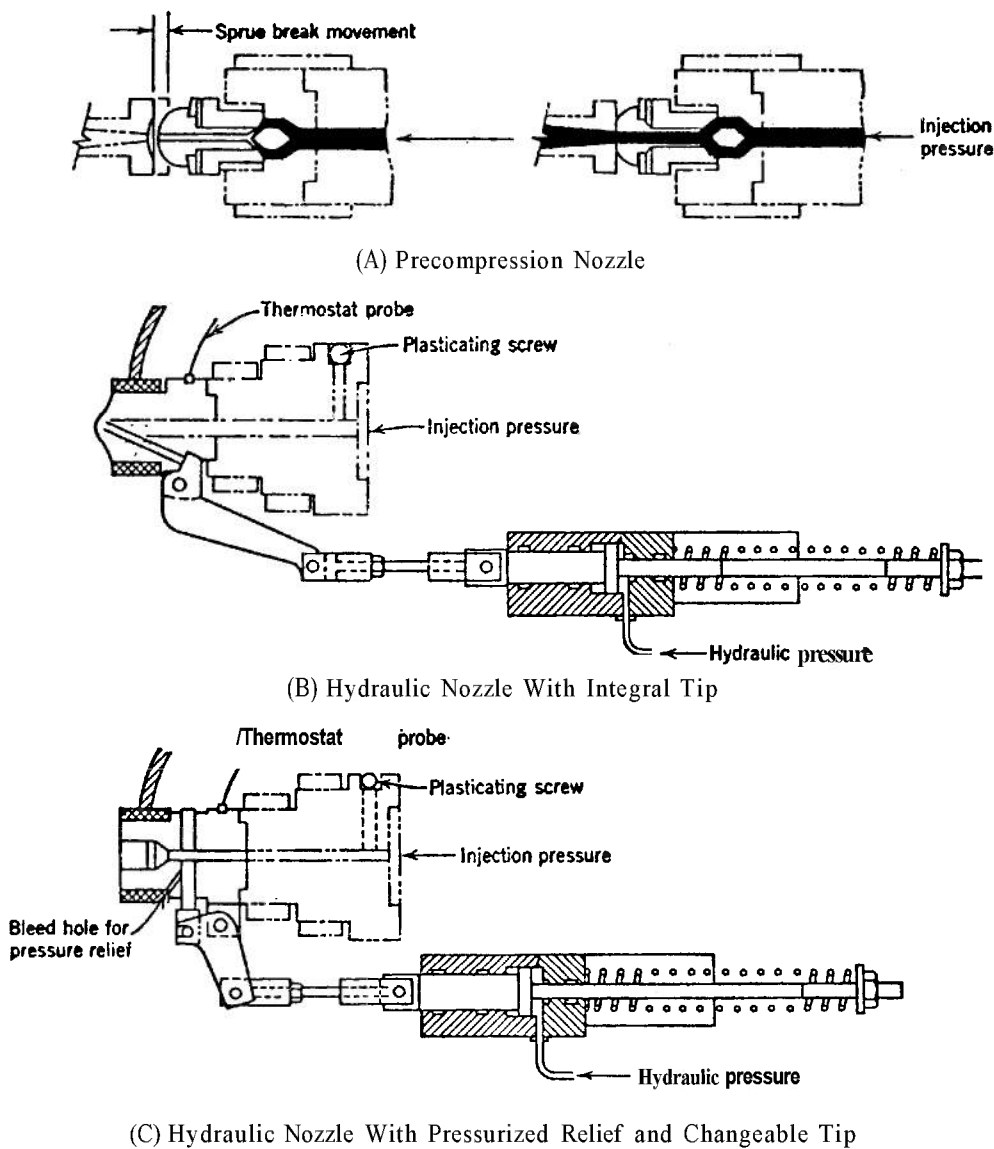
sure. Nozzles are so closely allied to molds that some types must be designed with the mold to perform correctly.

There are many types of nozzles — ranging from the simplest, smoothly tapered nozzles to valved types which include automatic, hydraulically actuated shutoff and check valves. They are as individualistic in design as the molds which are used in injection molding. Figs. 4-6 and 4-7 illustrate some typical nozzles.

Nozzles generally are made of tough, hard, tool

steels and beryllium-copper. They are built with sufficient mass and heat capacity so that they do not cool rapidly. Rapid cooling would cause the material to harden in the orifice of the nozzle. This causes such difficulties as plugging, contamination of the next shot, and incomplete mold cavity filling.

Generally, a nozzle with a large inside diameter ($7/16 - 1/2$ in.) is preferred for GRTP. The exit orifice is generally $1/4$ in. and the land should have a reverse taper of 2-3 deg. Heat sensitive



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Figure 4-7. Operation of Nozzles³

resins such as PVC and FEP should have a straight through orifice of 1/4 in. with a 2-3 deg reverse taper. The larger openings permit material to build up around the inner wall of the nozzle. This layer of material acts as an insulator which prevents the melt in the center from overheating and causing degradation (see Fig. 4-8). Once the material is flowing through the nozzle, the power input to the nozzle band can be reduced by approximately 50% or low enough to avoid material oozing.

Shutoff nozzles are used to prevent nozzles from leaking into empty molds or when the nozzle is retracted from the sprue bushings. Valves of all kinds—i.e., spring-loaded ball check valves, hydraulically and mechanically operated needle valves, and rotary valves—have been incorporated into nozzles.

A shutoff ring that involves a closure of a sharp corner against a flat surface is recommended for reinforced thermoplastics (see Fig. 4-9). This provides a positive cutoff should some of the fibers be trapped in the closure.

Valve gating nozzles used in sprueless molding also belong in the general category of shutoff nozzles, as do the nozzles which are used for impact molding.

Gating nozzles, hot-runners and insulated runner molds, nozzle manifolds, and valve gating nozzles are used for obtaining sprueless moldings. Elimination of the sprue and runner system reduces costs through scrap and labor savings.

A gating nozzle is a nozzle with a small opening which forms a gate at the junction of the mold cavity (see Fig. 4-10). The nozzle takes the place of

the sprue and runner system, and shoots the melt directly into the cavity. Orifice diameters range from 0.020-0.060 in. which allow the molded part to tear free of the material remaining in the nozzle.

Gating nozzles are also used to terminate nozzle.

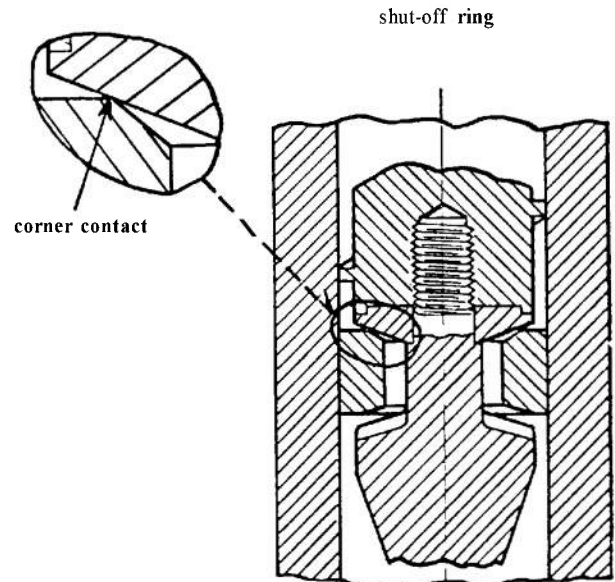


Figure 4-9. Shut-Off Ring'

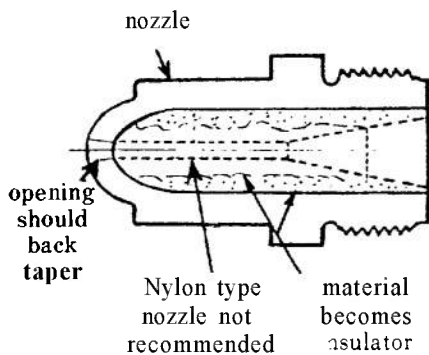


Figure 4-8. Suggested GRTP Nozzle'

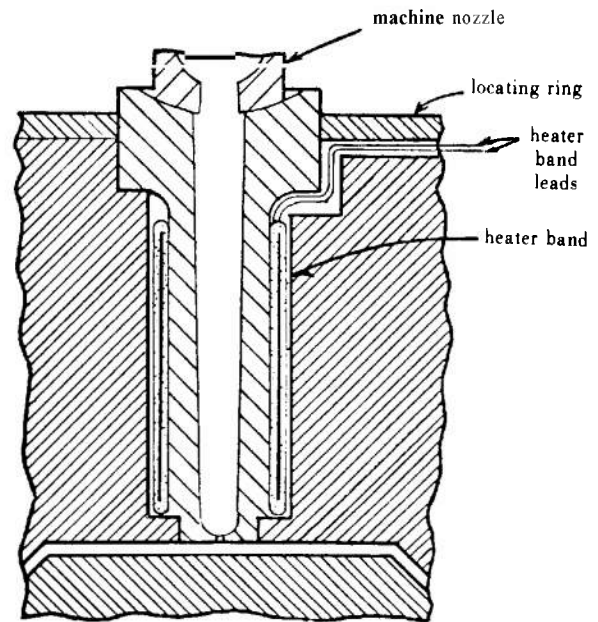


Figure 4-10. Hot Nozzle Extension'

zle manifolds. These units, usually in the shape of tubular structures, are attached through a "tee" section to the heating cylinder in place of the standard nozzle. Since a manifold is essentially an extension of the injection cylinder, it must be heated and occasionally also insulated, and must have its heat controlled by separate instrumentation. Uniform heat must be maintained on all legs of a manifold to prevent unbalanced flow.

Multiple nozzle manifolds have been used with high-production sprueless molds in completely automatic molding operations. The problem of temperature and pressure balance increases as the number of cavities in the mold increase and as the mass of each molding increases.

Another means of obtaining sprueless moldings is with valve-gated nozzles in impact molding. Valve-gated nozzles are operated by solenoid, hydromechanical lifters, or hydraulic ram lifters. In this method, a valved nozzle is programmed to remain closed while pressure is built up in the heating cylinder. Under high pressure, e.g., 15,000-20,000 psi, the plastic melt is slightly compressed. After the melt has reached a given pressure, the nozzle valve is opened; and the molten charge is forced through the nozzle orifice, rapidly filling the mold cavity. These nozzles close off and separate the molding from the material in the nozzle.

Advantages gained by filling a mold rapidly are increased production, and stronger and tougher molded parts. The latter results from the elimination of "frozen-in" stresses through the rapid and turbulent filling of the mold, which prevents orientation of polymer chains and glass fibers along flow lines.

4.2.2.5 Clamping

The clamp of an injection molding machine must have sufficient locking force to prevent the plastic melt, moving at high pressures, from forcing apart the mold halves. If the mating surfaces of the mold are forced apart even a few thousandths of an inch, fluid plastic will flow or flash across the mating area. The amount of clamp force depends upon the projected area of the molded part and the viscosity of the plastic melt at the final mold fill stage.

For extended tool life, the clamping pressure for each part job should be the lowest possible to prevent flashing. However, a clamping force of 5 to 10 tons per square inch of projected part area

should be available. This is 50 to 100% more clamping force than is necessary for the nonreinforced thermoplastic part.

There are many methods used for clamping the mold but most are variations of the following types: straight hydraulic ram; hydraulically actuated toggle; hydraulically actuated toggle for closing speed, with a secondary hydraulic ram for final lockup; and mechanical clamp with crank-type bull gears. The two most popular mechanisms are the fully hydraulic clamp and the hydraulically actuated toggle.

Most machines incorporate low pressure mold closing systems. These prevent damage to molds if parts are not fully ejected before the next mold closing. Pressure in the link end cylinder of an injection molding machine shifts to low just before the mold halves touch. If an obstruction is encountered, the closing action stops and a warning signal (such as a light or bell) alerts the operator that the mold must be cleared.

The following terms are used in describing the clamping capabilities of molding machines:

1. Clamping force in terms of tons
2. Clamping stroke—the maximum distance in inches the moving platen will move
3. Maximum daylight—the farthest distance in inches the platens can be separated from each other
4. Minimum mold thickness—the closest distance at which the two platens can meet without losing pressure
5. Clearance—distance in inches between the tie bars which is a determining factor in mold size
6. Clamp speed—movement in inches per minute
7. Knockout stroke—maximum distance in inches for knockout system.

Since injection molding clamping functions are fast and can be dangerous to the operator, certain safety features are required. An interlocked sliding gate at the front of the machine protects the operator. The interlocks are electrical, hydraulic, and mechanical.

The electrical system is tied into the die close control system and prevents the operation of this system with the safety gate in the open position. The hydraulic system is a pilot valve placed between the die close four-way valve and its solenoid control valve to prevent shifting of the four-way valve with the safety gate open. The mechanical system consists of some form of mechanical interference bar that physically prevents the

mold from closing with the safety gate and the press open.

4.2.2.6 Ejection Systems

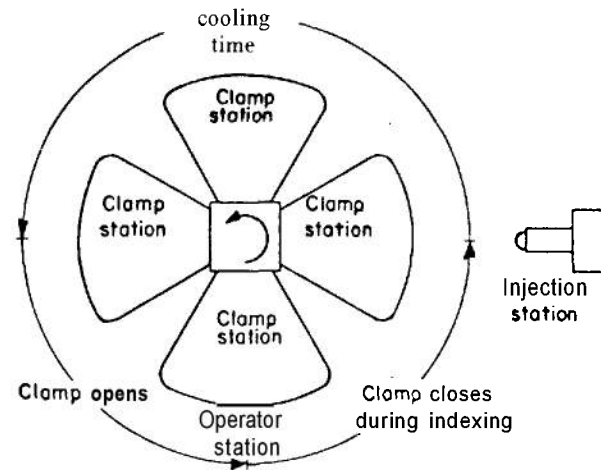
A knockout system is required to eject the part from the mold (see Chapter 7 "Mold Design"). On most machines there is an adjustable stationary ejector plate containing ejector bars which go through the movable platen. As the mold closes, the ejector bars go through the holes in the back platen of the mold, contact, and stop the mold knockout plate. The rest of the mold continues to close to a predetermined distance and stops. A superior method to activate the knockout system is by use of hydraulic cylinders. This permits advancing or retracting the knockout system with any speed or force. This can be particularly useful in cam and insert molding.

4.2.2.7 Special Injection Molding Machines: Insert Molding, Index and Rotary Machines, and Multicolor Molding

There are many designs of special injection molding machines. The need for insert molding has led to the development of a shuttle table machine. This is a vertical machine with one core plate attached to the movable platen. Two identical cavities are mounted on the shuttle table. While one set of cavities is molding, the empty mold is loaded with inserts. When the first molding cycle is completed, the mold slides out and the second mold slides under the force and the first cycle molded part is removed and loaded with inserts.

Generally, however, multiple station machines consist of a reciprocating screw horizontal machine with a round indexing table with four or more stations to which bottom mold halves are clamped. In this instance only one top mold half is used. Another design of rotary table machine employs four complete molds, one at each indexing station (see Fig. 4-11).

Fig. 4-11 illustrates the 4-stage cycling of the rotary turntable machine. Rotary turntable machines are available with from two to twelve stations, platen sizes up to 24 in. by 29 in., with vertical clamp design and clamping pressures from 385 - 880 tons. The clamping mechanism is fully hydraulic. Shot capacities range from 26 - 267 oz. Machines are also available with metered shot control that permits injection of a different shot



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Figure 4-11. 4-Stage Cycling of the Rotary Turntable⁶

volume and with variable injection pressure at each station. Therefore the equipment can accommodate different molds at each station for maximum flexibility. Tiered molds can also be used for additional productivity.

There are also sophisticated variations — machines with dual injection heads that can inject two different materials or colors at several stations. With this equipment one color can be injected into a cavity and filled to a predetermined block off or seal. At a later station a second color is injected after a relative motion has taken place within the mold. Certain specialized products or components lend themselves to this two-color or two-material process. In this type of molding, temperature and pressures are critical, particularly when good knit and adhesion are specified. In most cases a 12-station machine is used, with injection at the first and sixth stations.⁶

4.2.3 AUTOMATION

There is some degree of automation in every molding plant. The degree of automation will vary with complexity of the part, quantity of production, and available facilities and accessory equipment. Resin can be delivered in railroad cars and pumped into large silos adjacent to the molding plant. The material can be pumped inside the plant where it is automatically fed into individual machine hoppers. Here it is dried, me-

tered, and mixed with regrind if desired. (There will be no scrap for regrind if hot runnerless molds are used.) Depending on the applications, some molded parts can be automatically conveyed, inspected, counted, and packaged.

Automatic molding usually produces better quality parts more rapidly but does not eliminate operators entirely. An operator usually is present to monitor machines or perform secondary operations. There are several basic requirements for an automatic injection molding operation, namely:

1. The machine must be capable of consistent repetitive action. All molded parts, gates, and runners must be ejected automatically. There is usually some method of separating runners and gates from molded parts when runnerless molding is not used (i.e., wiper mechanisms, air blast, etc.). Some systems weigh the part after ejection and stop the machine or sound an alarm on off-weight parts.

2. A means for automatic shutoff and/or alarm when a part is stuck in the machine is required. All machines used automatically must have a low pressure closing system which prevents the machine from closing under full pressure if there is any obstruction between the dies.

Most of the controls used today in injection molding are aimed at controlling the process rather than the event. For example, rate of fill, pressure, and temperature can be controlled by some sort of analog or analog digital type system, reading either pressure, temperature, position, and/or other variables. Cavity pressure is measured in many systems.

Computers may be used in these systems to store data or make calculations which alter the machine conditions which control the process and/or the events of one machine or many machines.

There is no suitable instrument to measure plastic melt viscosity continually. However, viscosity depends on temperature. Therefore the measurement and control of temperature is substituted for the measurement and control of viscosity. This is the procedure used in automatic control.⁵

The use of solid-state controls has simplified present computer control. Automation can cover a range of computer sophistication. A computer can be a small relatively inexpensive unit developed just for controlling molding machines.

The control of injection temperature, pressure, and speed is required to make consistent quality

parts. To achieve this, all other conditions on which they depend—such as mold temperature, screw speed, clamping pressure, and time delay between shots—must also be controlled. Present technology is available to monitor all these systems as well as to program them for automatic control.

Some of the advantages of monitoring, comparing, and automatically changing machine conditions are:⁵

1. Better mold parts
2. More consistent parts
3. Fewer rejects
4. Faster production
5. Less dependence on labor and man-made judgments
6. Closer tolerance parts
7. Easier automation.

The theory of process and computer control is relatively simple. The processing of parameters is measured and translated into computer language. The computer then compares the actual data with the programmed data.

In a monitoring system, a discrepancy beyond the allowable programmed limit will sound an alarm or shut off the machine. In a feedback system, the error signal will result in a change of one or more of the machine settings, depending on the programmed instructions. Designing appropriate programs is a difficult part of computerizing the equipment.

An intrinsic advantage of injection molding is its ability to produce economically large numbers of parts, thus a likely candidate for automatic processing. Handling, sorting, and protecting the part must be considered in the beginning of the molding operation. Handling encompasses removing the part from the machine or the machine area as well as jiggging, fixturing, and secondary operations. This is particularly true of parts to be used on automatic assembly equipment.

In automatic molding, parts either fall directly into a container or are removed from under the mold by specialized belt type conveyors. From the conveyor they can be routed to sorting, inspection, packing, or another operation. Automatic handling of small parts is not unique to the molding industry. Extensive systems have been developed and are readily available commercially.

The introduction of larger machines and parts that weigh over 30 lb requires special handling techniques. Various shuttle systems have been developed. One promising method of handling

these parts is the use of industrial robots. They have movable arms terminating in some tool such as suction devices and claws which can grasp the plastic. They are usually hydraulically powered and electronically controlled. Sometimes they can be used on more than one machine, depending on their proximity and the cycling.

For additional information the interested reader is referred to the open literature which contains many fine articles on computerized injection molding.

4.2.4 AUXILIARY EQUIPMENT

4.2.4.1 Direct Powder Molding

Direct molding, the introduction of a dry blend of chopped strands and powdered polymer, is practiced by some molders. In this type molding a device for producing, conveying, and metering the dry blend is necessary.

Mixing can be accomplished in ribbon blenders and drum tumblers; however, a plough-type mixer is suggested. This type mixer can produce a homogeneous blend in a short time (15-30s) with undue fiber breakage.

Dry blends can be transported to the molding area manually or via modified pneumatic systems. Vacuum systems are not desirable. A tube spiral wire conveyor has been used successfully to transport dry blend from the floor level to an overhead hopper. A bulk loader operating from a 1000-lb metal container, the contents of which is dumped into an auger feed system, has also been used. The augers have been designed especially for conveying blends.

Dry blend can be introduced into the throat of the machine in two ways from the conventional hopper and directly metered into the throat of the machine. In the latter method an open double-spiral auger feeder can be used.

4.2.4.2 Pellet Blending

The use of concentrated pellets (80% glass-reinforced resin) requires blending with unreinforced resin for the appropriate glass/resin system. Such materials can be blended either in barrels or on automated mixing systems such as a two-screw proportioning system. Blending takes only 2 - 3 min. It is important not to overblend since this will cause degradation of the glass fibers.

4.2.4.3 Color Blending

The economy of purchasing a large quantity of uncolored resin can more than offset the cost of coloring. Scrap material can also be reblended to suit a desired color. The process of blending color (pigment) with the uncolored resin, usually called dry coloring, can be accomplished by tumbling in a drum. The drum apparatus is relatively inexpensive.

Color concentrates are also used for some materials. Pellets of plastic containing high concentration of color are mixed with the clear pellets in a ratio of about 1:10 for plunger machines and 1:20 for screw machines. The correct shade and intensity of color is ascertained by experimenting with the amounts of colorant used and the length of tumbling time'.

When pneumatic hopper loaders are used, color concentrates can be automatically proportioned and mixed with the clear pellets before they enter the hopper'.

4.2.4.4 Hopper Loaders

The hopper loader is effective in minimizing contamination, reducing spilling, and eliminating hand operations. Most loaders work on the air conveyor principle which employs tubes and a venturi jet to transfer the pellets from the carton to the hopper. The level of plastic pellets in the hopper is maintained automatically.

4.2.4.5 Weigh Feeders

The weigh feeder is an automatic balance which weighs a predetermined amount of pellets and transfers them to the heating cylinder during each cycle. In addition to the basic automatic balance, some weigh feeders have self-compensating devices which further regulate the amount of material charged to the cylinder.

4.2.4.6 Grinders

Grinders of all sizes are available to reduce molded scrap to useable granules. A 1/4- 3/8 in. screen should be used. As a rule of thumb, a maximum of 20% regrind can be blended with virgin material with no appreciable loss of properties. Scrap can be ground at the molding machine or at a control grinding location or both. Regrind must be kept dry and free of contamination before re-

cycling, and blended with virgin material before adding to the hopper.

4.2.4.7 Dryers

Hygroscopic materials must be dried in a dehumidifying oven or hopper before molding, even if they are packaged dry and in moisture-resistant containers. Since hot air has a higher moisture capacity, it is possible to actually introduce moisture to the material with hot air circulating ovens without dehumidifiers. The dehumidifier can be either a mechanical type or a chemical desiccant.

In oven dryers the plastic is spread on thin layers (less than 1/2 in.) in trays and exposed to hot air circulating in a closed system through a dehumidifier. The drying time of hygroscopic material depends on the resin system but is usually 2 - 4 h at the recommended temperature (see Table 4-1). The oven or hopper should be capable of maintaining a temperature of at least $250^{\circ} \pm 5^{\circ}\text{F}$. It may also be necessary to dry non-hygroscopic resins to eliminate surface moisture which has condensed onto the pellet surfaces. If moisture exceeds a permissible amount, it will be converted to steam in the injection cylinder and cause blisters and specks on the surface as well as internal voids.

Filtered hopper dryers generally are used except when long drying times are required. This type dryer replaces the standard machine hopper. Generally, it forces hot dehumidified air through the plastic pellets in the hopper section through a closed air circulating system.

4.2.4.8 Mold Temperature Regulators

Mold temperature regulators are used to both add and remove heat from the mold. Mold temperatures for reinforced resins are generally higher than for the nonreinforced ones. Higher mold temperatures promote flow and give a better surface finish. A slightly higher mold temperature will not increase cycle time. Standard mold temperature control equipment, such as pumps, storage tanks, immersion type heaters, thermostatic controls, and pyrometers, are satisfactory. Molds should be designed with good temperature control of core and cavity faces by means of adequately sized and spaced heating elements.

Choice of a temperature-control medium will depend on the resin being molded. For instance,

oil or electric-cartridge heaters are needed when heating a mold for fluorinated ethylene-propylene (FEP) or polysulfone where temperatures of 205°C (400°F) and 150°C (300°F), respectively, are used. It is preferable to have independent temperature control for each mold plate. This gives flexibility, especially in long cores, where it is often desirable to maintain each core at a temperature different from that of the cavity.

4.2.5 INJECTION MOLDING PARAMETERS

4.2.5.1 General Purpose Glass-Reinforced Resins

As previously stated, GRTP can be processed on either screw or plunger (ram) type machines. However, because reciprocating screw machines are preferred and generally used today, this paragraph and processing data and discussion presented in Table 4-1 are applicable to reciprocating screw machines.

All hygroscopic resin systems must be oven or hopper dried according to suppliers' instructions (Table 4-1) before molding. In some instances, the pellets must be kept at certain temperatures in a dehumidifying hopper after predrying and during molding. If any surface moisture exists, all systems must be predried in order to prevent damage to the moldings.

In most instances previous molding materials should be purged from the machine before introducing a new resin system. Typical polymers suitable for purging the machines are nonreinforced polyethylene, polypropylene, and polystyrene. When the cylinder is completely free of the material being purged, cylinder temperatures can be brought up to the recommended molding temperature.

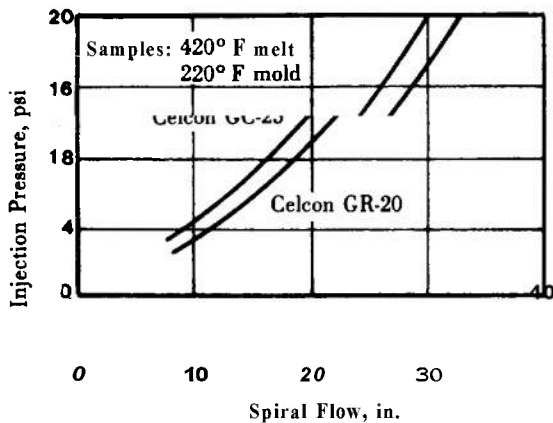
Brief shutdown periods (10-15 min) require the temperatures to be lowered somewhat and the machine purged periodically, preferably on cycles to prevent excessive residence time in the cylinder. For longer shutdown periods the cylinder heaters should be turned off but the nozzle heat kept up to the recommended temperature and the machine purged. When the material temperature is reduced to recommended temperatures, the machine can be turned off completely. When shutting down a screw machine, the screw should be left in the forward position. If a mass of molten material is left in front of the screw at shutdown, restarting the machine will be delayed until the slug in front of the screw is remelted.

Normally with GRTP the rear barrel zone is almost as hot as the rest of the barrel to minimize fiber breakage.

Melt flow is influenced by fiber content and concentration, wall thickness, melt temperature, and pressure (see Figs. 4-12 through 4-20).

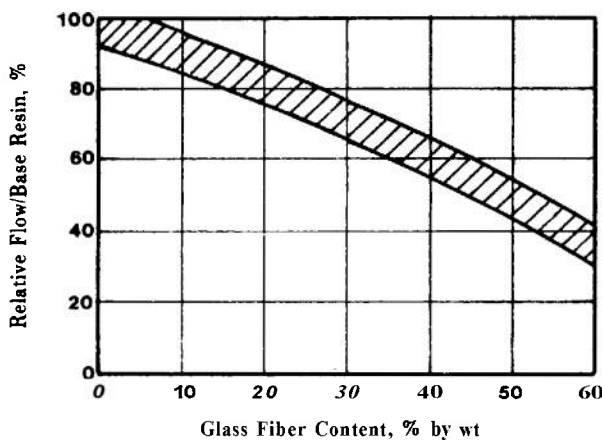
As a result of the increased melt flow of reinforced systems, the injection pressure, mold temperature, and cylinder temperatures are increased over nonreinforced systems.

For the most part glass-reinforced materials



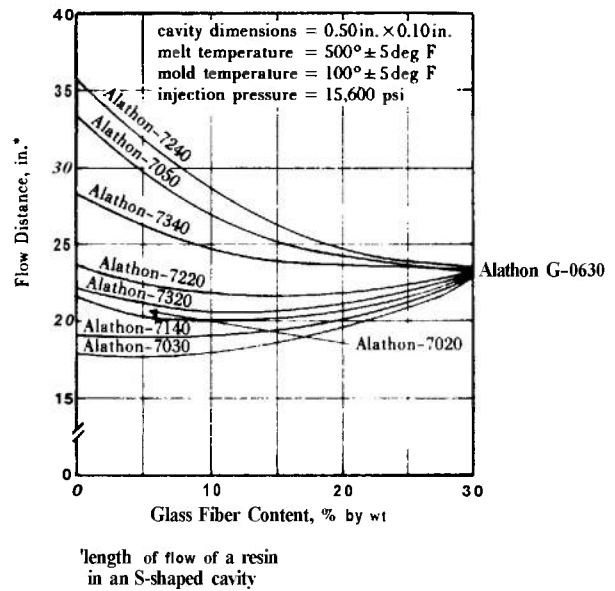
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Figure 4-12. Melt Flowability of Glass-Reinforced Celcons⁷



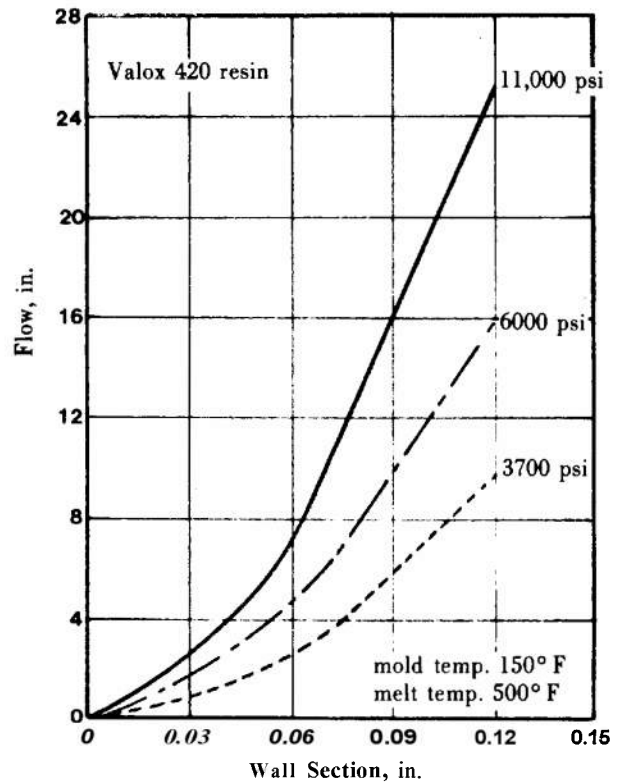
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Figure 4-13. Spiral Flow vs Glass Content in Fortified Nylons 6, 6/6, and 6/10 Resins¹



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Figure 4-14. Melt Flow Under Injection Molding Conditions vs Glass Fiber Content for Alathon Resins¹



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Figure 4-15. Spiral Flow vs Wall Thickness¹¹

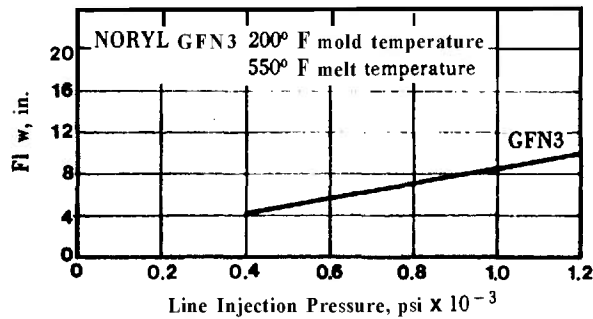
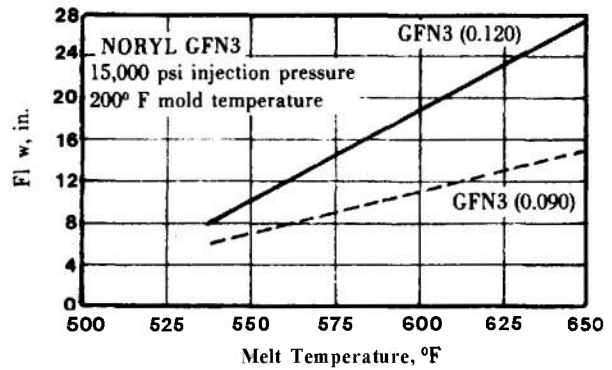
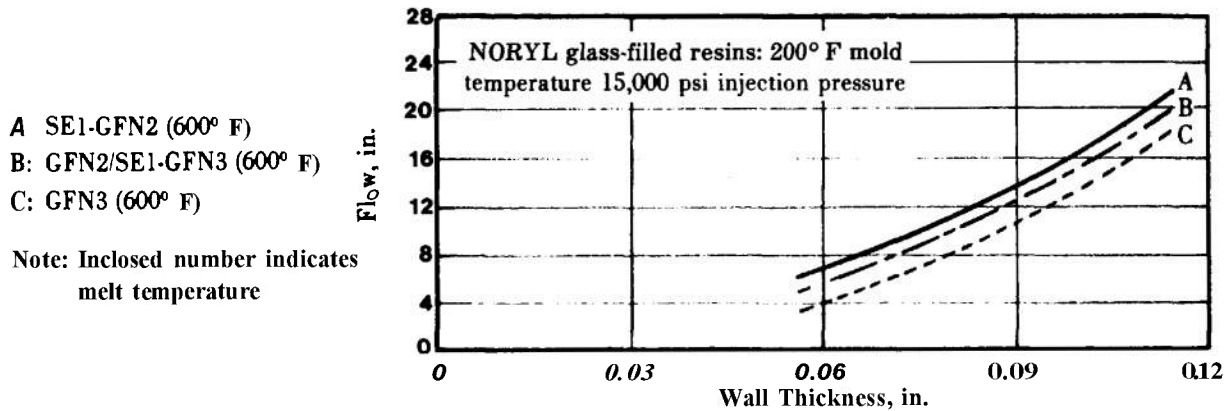


Figure 4-16. Melt Flow vs Injection Pressure (0.09-in. Wall Thickness)"



Note: Inclosed number indicates wall thickness

Figure 4-18. Melt Flow vs Melt Temperature"



- A SE1-GFN2 (600° F)
- B: GFN2/SE1-GFN3 (600° F)
- C: GFN3 (600° F)

Note: Inclosed number indicates melt temperature

Figure 4-17. Melt Flow vs Wall Section Thickness"

set up faster than nonreinforced. The surface appearance of parts is directly related to injection pressure and mold temperatures. Higher mold temperatures are used to obtain superior surface gloss and uniformity. Low mold temperatures are sometimes employed to help prevent sinks or warpage. Because of the rapid setup time, short cycle times can be expected (usually 25-35% less than nonreinforced materials).

Fast injection speed is desired because of the rapid solidification. Cavities should be filled as rapidly as possible to minimize glass orientation and enhance weld-line integrity.

Low screw speeds and minimum back pressure are recommended. Back pressure need only be high enough to compact the molten material in front of the screw as the screw rotates and re-

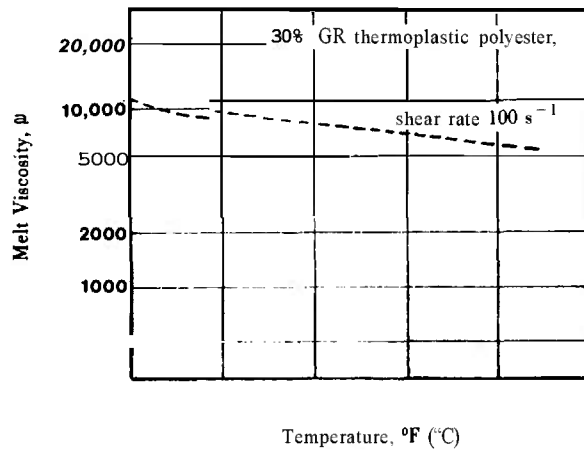
tracts. Screw speeds usually are operated between 25-75 rpm.

Best results normally are obtained when shot weight (material charge) is 50-80% of the rated machine capacity.

Clamping pressure depends on part wall thickness and length of flow. Generally 3-5 tons per square inch of projected area are adequate to maintain tolerances and avoid flashing.

Regrind can be used in most systems. However, since regrinding will affect the glass fiber length and mechanical properties, it should be limited to 20-30% in most cases. When impact strength or critical performance is required, regrind should not be used.

Specific recommendations for molding G RTP are given in Table 4-1.



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Figure 4-19. Melt Viscosity of Valox vs Temperature (Relatively insensitive to temperature changes in the normal processing temperature range)¹²

4.2.5.2 Blending Glass Concentrated Pellets

The following equation is helpful in determining the quantity **A** of unreinforced pellets required to obtain a desired glass percentage with glass concentrated pellets:

$$A = \frac{B}{C} - 1, \text{ lb} \quad (4-1)$$

where

B = glass content of concentrated pellets, %

C = desired glass concentration of end product, %.

The quantity **A** is the number of pounds of unreinforced material that should be added to one pound of concentrated pellets to achieve the desired end percentage.

For example, using an 80% glass concentrated pellet and desiring a 20% glass product would require 3 lb of unreinforced resin, i.e.,

$$A = \frac{80}{20} - 1 = 3 \text{ lb of unreinforced resin.}$$

Pellets can be blended in either barrels or an automated mixing system such as the two-screw proportioning systems. Blending should take only 2-3 min. Overblending can cause reduced material properties as a result of glass fiber breakage.

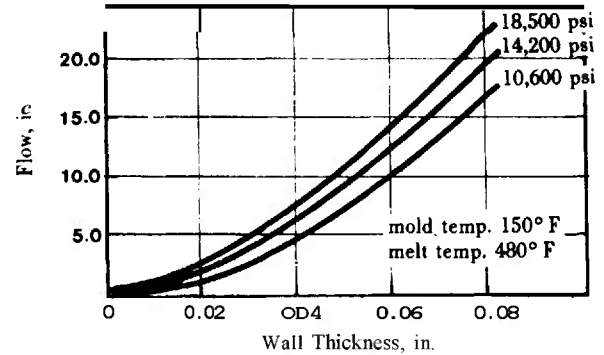


Figure 4-20. Flow vs Wall Thickness Celanex 3210 (Ref. 13)

4.2.5.3 Special Molding Materials

A number of special materials have been formulated to provide flame resistance or improved lubricity. Such additives require changes in molding parameters, and specific parameters must be obtained from the material suppliers for each material.

For example, flame retardant additives act as flow aids and increase the flow length of the material. This will affect mold filling and part surface finish. Excessively high cylinder temperatures and long residence times can destroy the additives and cause corrosive gases which can attack equipment and harm molding operators. Some general recommendations for fire retardant materials are:

1. Use a general purpose screw with a 2 to 1 compression ratio.
2. Use a polyethylene type nozzle rather than a nylon type nozzle.
3. Vent molds adequately.
4. Do not use a small shot size in large shot equipment. This is to prevent long residence time.
5. Control nozzle drool by lowering nozzle temperature; not with positive shutoff nozzles.
6. If a delay in molding operation should occur, the machine should be purged at 2-min intervals to prevent degradation. If the delay is of some length, it is suggested that temperatures be lowered and the machine purged.
7. If a flame resistant compound is to remain in the cylinder over 5 min, or if a change in material color is observed, the cylinder should be purged. Adequate means of venting should be provided upon purging.

8. It is recommended that a base resin of the same type be used as a purging compound since other compounds may not be compatible with the flame resistant compound.

4.2.5.4 Safety

Most materials when overheated can cause burns, ignite flammable materials, release harmful vapors, etc. Resins should not be subjected to temperatures in excess of those shown in Table 4-1 without consulting the material supplier.

“Wet” nylon can splatter. Overheated acetal copolymer demands good ventilation. Thermoplastic polyester can give off toxic fumes if too hot. Accordingly, good safety practices are necessary with glass-reinforced materials as with any molding material. Caution also should be observed when regrinding glass-reinforced resins of any kind. Glass dust must be quickly and efficiently exhausted from the area to preclude harmful inhalation. Dust masks for personnel in grinding

areas are recommended. Glass fines can also be irritating to the skin.

These precautions are normal in the use of glass-reinforced resins and are being observed in molding plants today.

4.2.5.5 Molding Problems

Table 4-2 lists most of the molding problems encountered with GRTP and presents suggested solutions.

4.2.6 MACHINE WEAR

The amount of wear and expected life of the injection machine components are of great importance to the molder. Not only is the equipment rendered unserviceable but worn equipment can cause loss in plasticizing capacity and loss in injection pressure resulting in the inability of the machine to fill the shot or pack the shot properly. This produces unsatisfactory moldings.

TABLE 4-2. TROUBLE-SOLVING GUIDE FOR GRTP'S

Problem	Suggested Solution	Problem	Suggested Solution
Flash	<ol style="list-style-type: none"> 1. Stock too hot 2. Clamping pressure too low 3. Injection pressure too high 4. Inadequate mold supports 5. Decrease overall cycle 6. Improve mold venting 7. Check press platens for parallelism 8. Check mold closure for obstruction on parting line surface 	Short Shots, Poor Surface Finish	<ol style="list-style-type: none"> 1. Increase feed 2. Increase injection pressure 3. Use booster and maximum ram speed 4. Decrease cushion 5. Raise material temperature by raising cylinder temperature 6. Raise mold temperature 7. Increase overall cycle 8. Check shot size vs rated machine shot capacity; if shot size exceeds 75% of rated (styrene) shot capacity, move to larger machine 9. Increase size of sprue and/or runners and/or gates 10. Check restricted nozzle 11. Check runaway nozzle heater band 12. Increase injection speed
Sinks or Voids	<ol style="list-style-type: none"> 1. Pressure too low 2. Mold temperature too low or too high 3. Stock temperature too high 4. Entrapped gas—vent mold 5. Increase size of sprue and/or runners and/or gates 6. Land too long or short 7. Decrease cushion 8. Relocate gates nearer heavy sections 9. Dry material 10. Increase plunger forward time 11. Use booster 	Burning	<ol style="list-style-type: none"> 1. Stock too hot 2. Frictional burning—enlarge gates 3. Inadequate venting (trapped gases) 4. Decrease injection pressure 5. Slow injection speed 6. Decrease booster time 7. Decrease plunger speed

TABLE 4-2 (cont'd)

Problem	Suggested Solution	Problem	Suggested Solution	
Discoloration	1. Purge heating cylinder	Part Undersize	1. Use fast ram	
	2. Lower material temperature by lowering cylinder temperature		2. Increase pressure and plunger forward time	
	3. Lower nozzle temperature		3. Increase cylinder heats	
	4. Shorten overall cycle		4. Increase mold temperature	
	5. Check hopper and feed zone for contaminants		5. Open runner and gates	
	6. Check cylinder and plunger or screw fit for excessive clearance	Part Oversize	1. Decrease pressure	
	7. Provide additional vents in mold		2. Increase mold temperature	
	8. Move mold to smaller shot size press		3. Shorten overall cycle	
	9. Check temperature controls and instruments	Weld Lines	4. Decrease cylinder temperature	
	10. Moisture-dry material		1. Stock too cold	
	11. Cracked check ring		2. Injection speed too slow	
	12. Excessive back pressure—reduce to 50-150 psi		3. Mold too cold	
	13. Areas of hang up; hot spots		4. Relocate gates	
Warpage, Part Distortion	1. Equalize temperature in both halves of mold	Jetting	5. Dry compound	
	2. Observe mold for uniformity of part ejection		6. Add larger vent or overflow puddle	
	3. Check handling of parts after ejection from mold		7. Change gate location to alter flow pattern	
	4. Increase plunger forward time	Sticking in Cavities	1. Stock too cold	
	5. Try increased pressure and reduced pressure		2. Injection too fast	
	6. Try higher and lower mold temperature		3. Gates too small	
	7. Increase die closed time		1. Decrease injection pressure	
	8. Lower material temperature		2. Decrease plunger forward time	
	9. Set differential mold temperatures to counteract warp due to part geometry		3. Decrease booster time	
	10. Jig the part and cool uniformly		4. Adjust feed for constant cushion	
	11. Relocate gate for proper fiber glass alignment		5. Increase mold closed time	
Poor Dimensional Control	1. Set uniform cycle times		Sticking in Sprue Bushing	6. Lower mold temperature
	2. Maintain uniform feed and cushion from cycle to cycle			7. Decrease cylinder and nozzle temperature
	3. Fill mold as rapidly as possible	8. Check mold for undercuts and/or insufficient draft		
	4. Check machine hydraulic and electrical systems for erratic performance	9. Use a proper mold release		
	5. Increase gate size	1. Decrease injection pressure		
	6. Balance cavities for uniform flow	2. Decrease plunger forward time		
	7. Reduce number of cavities	3. Decrease booster time		
	8. Check heater bands burned out	4. Increase die closed time		
	9. Excessive cylinder clearance	5. Increase mold temperature at sprue bushing		
	10. Check cracked ring	Lack of Gloss	6. Raise nozzle temperature	
	7. Check sizes and alignment of holes in nozzle and sprue bushing (hole in sprue bushing must be larger)			
	8. Provide more effective sprue puller			
		1. Mold too cold		
		2. Low injection pressure and speed		
		3. Injection hold pressure time too short		

TABLE 4-2 (cont'd)

Problem	Suggested Solution
Nozzle Drool	<ol style="list-style-type: none"> 1. Lower nozzle temperature 2. Lower material temperature by lowering cylinder temperature 3. Decrease residual pressure in cylinder by: <ol style="list-style-type: none"> a. Reducing plunger forward time and/or back pressure b. Increasing "decompress" time (if press has this control) 4. Decrease die open time 5. Use nozzle with positive shutoff valve
Nozzle Freeze-Off	<ol style="list-style-type: none"> 1. Raise nozzle temperature 2. Decrease cycle time 3. Increase injection pressure 4. Raise mold temperature 5. Use nozzle with larger orifice

Many factors contribute to machine wear such as the corrosiveness of coupling agents, additives, and resin systems; the improper choice of materials for screws, barrels, and shutoff valves; and poor component design. Glass fibers in the normal processing of precompounded material are suspended in a melt of resin and do not cause excessive wear. However, improperly handled, they can multiply wear problems¹⁴.

4.3 SOLID-PHASE FORMING AND COMPRESSION MOLDING

4.3.1 DEFINITION

Most commercial processing methods form GRTP into useful objects by shaping viscous molten plastic under pressure in a cold mold. In solid-phase forming, glass-reinforced sheet or billet is heated below its melt temperature and formed while in a solid state by metalworking techniques. These techniques are primarily forging and stamping.

Cold forming is a forming process performed at room temperature with unheated materials and tooling. This process is not relevant to GRTP but is mentioned here because it is often erroneously interchanged with solid-phase forming by the industry.

Compression molding is similar to solid-phase molding except the glass-reinforced materials are

heated to above their melt temperature and shaped by melt flow. The heated material has the consistency of wet cardboard due to the glass reinforcement. Unlike solid-phase forming, this permits parts with varying cross sections, ribs, and bosses.

It should be made clear that any evaluation of solid-phase forming and compression molding techniques with other processes (injection molding, rotational molding, etc.) must take into account the complete integrated process.

4.3.2 GLASS-REINFORCED MATERIALS

An essential requirement for solid-phase forming is to have the material in sheet or billet form. There are several ways to obtain the material for forming, most of which involve proprietary processes. The methods used include extrusion; alternating, fusing, and compressing layers of thermoplastic sheet or film and glass fiber mat, preformed glass, or chopped roving; mixing resin powder and chopped glass fiber, fusing, and rolling into sheet form; and impregnating glass reinforcement with hot-melt resins and drying to form a sheet.

The processor may purchase the sheets or billet from a supplier or prepare the material himself as an integral part of the processing technique. In this handbook, emphasis is placed on the forming operation without going into the details of material preparation because the processing is proprietary and this handbook is concerned only with discontinuous short (1/2 in. or less) fiber reinforced materials. The majority of materials used in compression molding are other than short fiber GRTP. They are predominantly continuous glass reinforced thermoplastic laminates and long fiber (over 2 in.) discontinuous thermoplastics.

Unlike injection molding, not all GRTP are suitable for solid-phase forming. To be successful, the polymeric matrix materials must possess sufficient ductility to deform the required shape at the forming temperature. The flow of the material under forming pressure must be such that local necking or cracking does not occur. At the same time the recovery, or "memory", characteristics must be low so that springback and recovery of time-dependent strains are minimized. Springback as used in forming technology refers to the recoverable deformations attained after a part is removed from the forming die and which occur within a relatively short period. Thus, poly-

mers such as polypropylene, nylons, high-density polyethylenes and rubber modified polymers (acrylonitrile-butadiene-styrene, polyvinyl chloride, styrene-acrylonitrile (SAN), etc.) can be easily formed while brittle materials such as polystyrenes and the acrylics cannot. On the other hand, soft rubbery polymers can be formed but the recoverable deformation is very large and results in excessive springback. To overcome this defect would require long forming cycles and an impractical tool design.

In solid-phase forming there is less movement of the material and the longer reinforcing fibers may be incorporated to produce structurally stronger parts.

Table 4-3 lists some commercially available **G RTP** sheet materials used in hot melt stamping or compression molding.

4.3.3 FORGING AND STAMPING

4.3.3.1 Forging

Forging is fabrication by bulk deformation of material in constraining dies by the application of force. Forging in its simplest form is illustrated in Fig. 4-21 — two opposing shaped punches mate in a common floating ring to form a closed die. With the upper punch raised, a preheated billet of specific weight and shape is placed on the lower

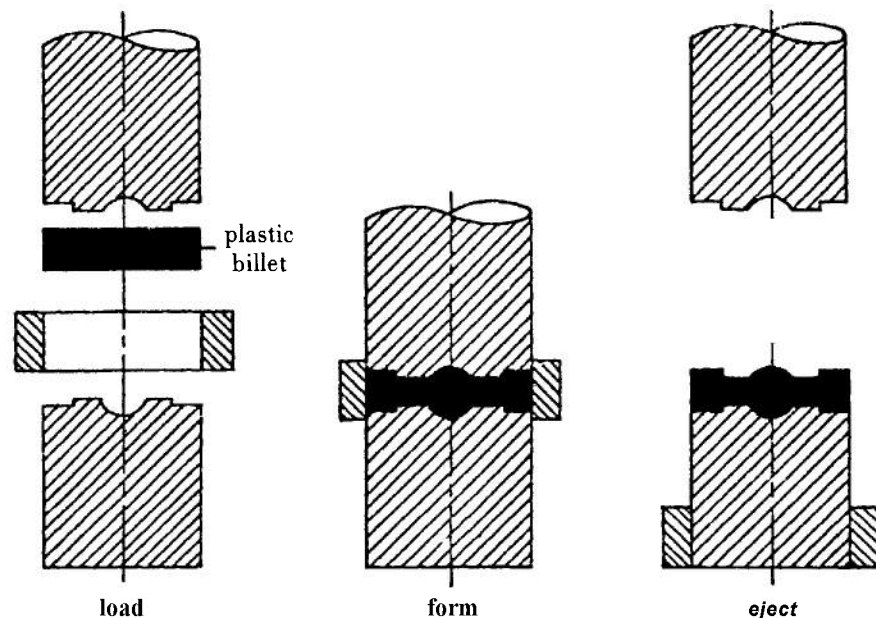


Figure 4-21. Forging Process¹⁶

TABLE 4-3. G RTP SHEET

Material	Trade Name	Company
Polypropylene	Adzel P101	G.R.T.L. Co.
SAN	Adzel A201	G.R.T.L. Co.
Nylon 6	STX	Allied Chemical

punch in the die ring. The upper punch closes and pressure is then applied, forming the billet to the desired shape. After a short dwell time the upper punch is raised, the die ring is pulled down over the lower punch, and the lower punch is raised to eject the forging.

4.3.3.2 Forging Parameters

Like all fabricating techniques, the forging process offers many variations in each step depending on the material selected and part requirements.

4.3.3.2.1 Temperatures

Optimum billet temperature for crystalline materials is at or near the crystalline melting temperature of the matrix and above the second-

order transition temperature for noncrystalline polymers.

A constant temperature throughout the billet must be maintained. Temperature variations can give rise to residual stresses, poor part filling, and differential recovery or springback.

Mold temperature is significant but less so than billet temperature. Difficulty is experienced in filling molds with cold tools because of the rapid surface chilling of the plastic.

4.3.3.2.2 Forming Cycle

Since the billet is in a solid state, no solidification time is required. It is necessary, however, to maintain a forging pressure for a period of time after the initial displacement of material. This is to permit the stress relaxation required to prevent recovery due to the plastic "memory" effect. The forming cycle—dwell time, forging pressures, and speed—will vary with part design, material used, and the temperature of the material. Since there is little published technical data or experience in forging, specific parameters must be determined by trial and error for each application. Some general observations concerning forging cycles are: higher forging pressures reduce cycle time; forging tonnage increases rapidly as the part thickness decreases; and metal inserts can be forged in place without affecting the cycle time.

4.3.3.3 Advantages and Disadvantages

4.3.3.3.1 Advantages

Some advantages of the forging process follow:

1. The typical forming cycle is much faster than conventional methods (excluding billet preheating time), and the speeds are essentially independent of part thickness.

2. The capability to form parts with very thick sections (1 in. or more) which cannot be made by any other method except machining.

3. Tooling is relatively inexpensive; forging tools cost about 35% of injection molding counterparts.

4. "Cold working" by deformation in the solid-phase forming increases the toughness and strength of formed parts. This improvement is generally proportional to the amount of cold working involved.

5. Forging produces parts with no flash or trim, sprue marks, weld lines, or shrink marks. This reduces scrap and permits good surface finish.

6. Thermal shrinkage of the solid material from its heated state to ambient is considerably less than that encountered for melt forming techniques.

4.3.3.3.2 Disadvantages

Some disadvantages of the forging process follow:

1. There is the extra cost of heating the billet. In fact, oven design and heating techniques are among the most important factors in high quality mass production.

2. Forging is a multiple step process and involves the added cost of producing and handling billet and blanks. Such costs vary widely with quantity and type of production.

3. Elastic recovery or springback must be taken into account in the selection of material, the process, and tooling design.

4. Part complexity is somewhat limited over the melt techniques but extra tool motions can be used to make more complicated parts. Also, stress whitening of the part can be a problem with some colors.

5. High temperature dimensional stability of formed parts is not as good as those formed by melt techniques. Part distortion temperature will vary with material, design, and processing conditions. However, solid-phase formed parts will revert completely to their original configuration when heated to temperatures in the vicinity of their glass transition temperature T_g .

4.3.3.4 Tooling

The material reportedly used for the most tooling has been a machinable grade of heat treated tool steel having a hardness of **34-42** on the Rockwell C scale. Since there is no metal-to-metal tool closure, close tolerances, or sophisticated cooling, the tooling costs are estimated to be about one-third of their counterparts for injection molding.

4.3.3.5 Stamping

Stamping is the formation of a shallow part by rapid application of force on preheated glass-reinforced blanks in matched metal dies. The blanks

must be larger than the die size, trimmed to part size in the die, and preshaped to avoid excessive trim.

4.3.3.6 Stamping Parameters

The blanks are usually heated to about 150°-205° C (300°-400° F) from one side via high intensity pulsed infrared ovens. Generally a heating intensity of 6-7 W·in.⁻² in 15-s on/off cycles is recommended. The blanks are then transferred manually or automatically via conveyors to the dies.

The top and bottom dies are heated independently to about 120°-150° C (250°-300° F). Dies are of hard tool steel with the part appearance surface mounted on the top platen. A vertical flash design with adequate guide pins, safety stops, and ejector system is suggested. Dies must have a shear edge of about 0.002-0.003 in. to trim the part in station.

Both mechanical and hydraulic presses can be used. However, fast closing hydraulic presses with fast pressure rise of a minimum of 500 psi are preferred. Dwell times range between 10-20s, depending on material and part thickness.

4.3.3.7 Advantages and Disadvantages

4.3.3.7.1 Advantages

Some advantages of the stamping process follow:

1. Large, high surface area parts can be stamped into shape rapidly on existing commercial equipment.

2. Finishing and tooling costs are relatively low, and sheet metal stamping presses can be used.

3. Glass fiber reinforcement is not reduced during stamping, permitting optimum properties.

4. Stampable materials produce isotropic parts which do not possess fiber orientation. This leads to more uniform properties across the part.

5. It permits high speed production of parts.

6. It permits insert molding in one operation.

7. Parts can be pierced, punched, trimmed, etc., after or during forming.

4.3.3.7.2 Disadvantages

Some disadvantages of the stamping process follow:

1. Mechanical presses must be modified from metal stamping to plastics stamping, i.e., the

bottom-dead-center position must be adjusted to suit the weight of the plastic charge. Overweight can jam and damage the press.

2. Parts are limited to shallow forms of uniform thickness without bosses, ribs, or thick sections. However, corrugated sections, molded-in lettering, embossing, and raised numbers are possible.

3. Sheet material is more costly than molding pellets.

4.3.4 COMPRESSION MOLDING (HOT FLOW STAMPING)

Four basic types of compressive molding have been developed—short flow forming, center flow forming, stack flow forming, and drape forming. The flow technique selected will depend on material and part design. Normally, the more flow introduced during molding the better the surface quality. However, more flow entails greater glass fiber orientation.

The four compression molding techniques are briefly described. It should be remembered that these techniques have been used almost universally with continuous or long glass fiber reinforcements and not with short fiberglass-filled materials. Therefore, only a brief description of the processes will be given here. The interested reader is referred to the bibliography for specific processing parameters.

4.3.4.1 Short Flow Forming

In this process the blank is smaller and thicker than the final part. During stamping the material will flow to fill out the mold without significant glass/resin separation. With a die design using telescoping edges, a flash free, trimless part is produced. This method is good for in-mold lamination of overlays and producing thin parts from thin sheets.

4.3.4.2 Center Flow Forming

Center flow forming, shown in Fig. 4-22, is used to produce parts with varying cross sections and those with larger part thickness tolerances. It is a versatile method and can be used alone or as a "hybrid" with the short flow method. It consists of two rolling banks of sheet which propagate in opposing directions. These banks produce the following effects:

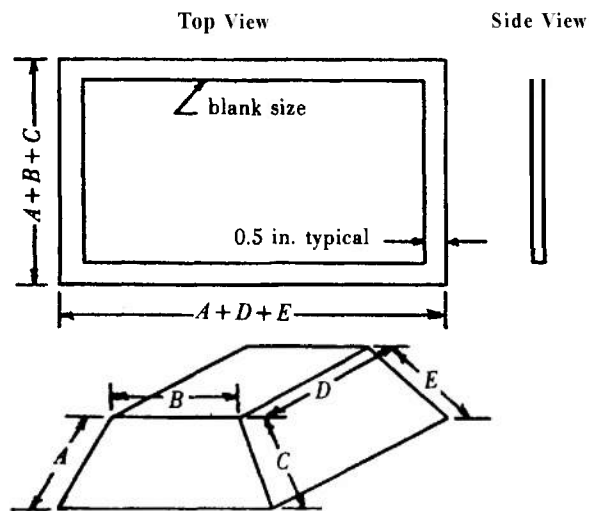


Figure 4-22. Center Flow Forming"

1. Sweep the air out of the die to eliminate air entrapment.
2. Permit thicker sections through the addition of material to the basic sheet.
3. Subject the resin to shear, thus lowering viscosity and aiding in wetting the glass fibers.
4. Wet the die surfaces which produces a good surface finish.

The effect of center flow can be obtained by adding a narrow strip to the center of the blank or cutting the blank in two and locating it in an overlapping configuration. The additional strip can be put on the blank prior to heating or it can be heated separately.

4.3.4.3 Stack Flow Forming

In this process several individually heated blanks are stacked on top of each other and then compressed. This permits the formation of difficult parts which require considerable flow. In this technique the glass fibers become oriented in the direction of flow and caution must be used to prevent weld lines and glass/resin separation. A balance must be found between (1) too high a blank temperature—which reduces glass orientation but promotes glass/resin separation, and (2) too low a temperature—which helps to maintain a homogeneous glass/resin distribution but accelerates glass orientation.

4.3.4.4 Drape Forming

In drape forming the heated blank is larger

than the part to be formed. The amount of oversize depends upon the part design and accuracy of sheet loading. This technique is used to produce very deep drawn, cylindrical parts free from folds and wrinkles. A spring loaded draw ring must be used to prevent wrinkle formation while the plunger or plug descends. The ring must never be made of metal since metal will chill the material too much. The rings must be made of a nonheat-absorbing material such as wood, or plastic material such as phenolic laminate. A draw ring restraint is illustrated in Fig. 4-23. The main disadvantage of drape forming is that it generates trim and all parts must be posttrimmed which requires an additional operation.

4.3.4.5 Advantages and Disadvantages

Additional advantages and disadvantages of compression molding over those specified previously for stamping are given.

4.3.4.5.1 Advantages

Some advantages follow:

1. Parts can be molded with varying cross-sectional thicknesses, ribs, and bosses.
2. Large size sheets can be lap-jointed to fabricate large parts.

4.3.4.5.2 Disadvantages

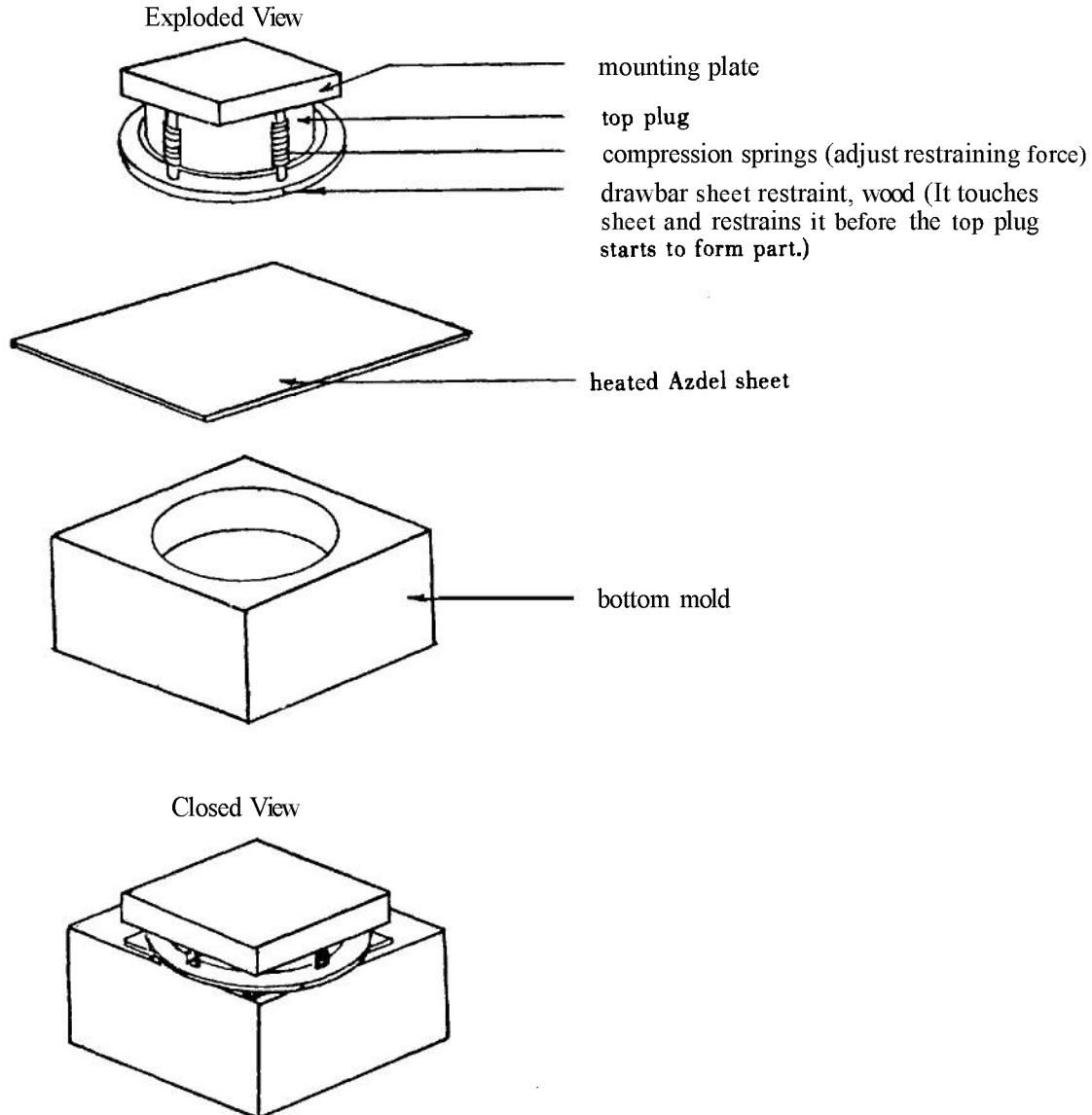
Some disadvantages follow:

1. Sheet material is difficult to heat and to support while heating. No clamps or double layers can be used which disturb the heat source or which would cause nonuniform heating.
2. Heated material is difficult to handle and transfer from oven to press.
3. Complete automation is difficult.
4. Glass fiber orientation results with lateral flow during molding. Resin/glass separation can occur if the material flows too far.
5. Shrinkage sink marks occur on the opposite side of bosses and ribs.
6. Some flow processes produce trim which is difficult to reclaim and reprocess.

4.3.5 EQUIPMENT

4.3.5.1 Blanking

The cold glass-reinforced sheet is prepared for



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Figure 4-23. Drawbar Sheet Restraint¹⁷

fabrication by cutting or shaping into blanks suitable for solid-phase forming or compression molding. The methods include metal shears, hand-machine cutting tools (bandsaws, saber saw, etc.), or stamping die in a punch press.

Blanking plastics with a press and die requires:

1. A long cutting stroke and high ram speed because of the shear characteristics of plastics.
2. Good press ram alignment due to the small punch-to-die clearance of metal dies. Three types of dies are used—progressive, compound, and steel rule. An accurate press feed is necessary with progressive dies. Feeding is not as critical

with compound dies; however, faster ram speeds are required. Positive stops must be incorporated in a steel rule die. Any overtravel of the ram will result in a rolled-over edge,

Appropriate part ejection is required with all three type die operations.

4.3.5.2 Heating Ovens

Pulsed (on-off) heating cycles with infrared ovens normally are used to heat composite sheets prior to forming. A fast rise, fast decay heat source is desired to obtain a fast, uniformly

heated material and to prevent thermal degradation. Heating time can be decreased significantly by selecting optimum wavelength, heater configurations, and high-low rather than on-off cycles.

A combination hot airinfrared preheat process may be useful in a rapid commercial operation where space is at a premium. A large inventory of hot sheets is maintained in a compact circulating hot air oven. A short conveyORIZED infrared oven can be used for a brief final heating step close to the stamping press.

There are many commercial infrared heat sources on the market. They differ in heat density, construction, voltage requirement, wave length, and heat up and decay time. The following is a list of lamps with the time to reach 230°C (450°F):

<u>Lamp</u>	<u>Time to Reach 230° C (450° F), s</u>
Super-high density tungsten-quartz, 540 kW•m ⁻² (50 kW•ft ⁻²)	10
High density tungsten-quartz, 270 kW•m ⁻² (25 kW•ft ⁻²)	26
Low-density tungsten-quartz, 50 kW•m ⁻² (4.5 kW•ft ⁻²)	58
Low-density nichrome-quartz	200.

An oven using a T₃ tungsten/quartz lamp (Fos-toria Fannon Oven Company) with opposing bands of polished aluminum reflectors has been used successfully to heat Adzel sheet material. The material is supported and transported on a wire grid. Details can be obtained from Ref. 15.

4.3.5.3 Materials Handling

Some sort of materials handling is required to transfer the sheets from receiving, storage, and blanking into the oven and to and from the die. Cold sheet can be handled similar to metal sheets. It can be stacked on pallets and moved with forklifts. It can be vibrated, slid, pushed, and vacuum picked.

Nonsticking conveyors and endless wire loop

transport systems are used to transfer the blanks to and from the heating ovens and dies. The dies can be fed via vacuum cup mechanisms or bottom fed feeders, provided the stack is kept high enough to assure flatness of the bottom blank. All feeders must be synchronized with the oven.

Hot blanks can be transported via mechanical clamps (of low heat transfer material) or vacuum systems. Part removal from the dies is accomplished by an ejection mechanism.

4.3.5.4 Dies

Normally a compression-molding mold is equipped with telescoping edges and mounted into a rugged, heavy duty metal stamping die. Stamping dies need substantial built-in guidance systems because stamping presses do not provide adequate guidance.

Dies should not close against stop blocks or other restraints. The blank must be the only stop the die sees when stamping. Safety stop blocks, used to prevent empty die halves from crashing against each other, should be designed to provide a 0.020-in. distance between die halves.

Dies are heated with circulating fluid or electric heaters and water cooled. They are usually constructed of Rockwell RC 60 or higher steel.

4.3.5.5 Presses

Both mechanical and hydraulic presses can be used to forge, stamp, and compression-mold glass-reinforced sheets. However, to successfully stamp composites between cold, matched metal dies the presses must have a pneumatically or hydraulically operated clutch and brake, tie-rod construction if over 60 tons, and must run between 6 and 30 strokes per minute (spm). Hydraulically operated presses must have an adjustable stored energy system to form at a prescribed force level¹⁹.

Table 4-4 presents the relative advantages and disadvantages of each type of press. The main advantages of mechanical presses are their availability in high tonnage capacities (upto 5000 tons) and the high rate of pressure rise inherently achievable. Large capacities become important when compression molding large parts such as automobile hoods or roofs. Minor disadvantages of these presses lie in the modifications that must be performed on them to convert from metal stamping to plastics processing.

TABLE 4-4. MECHANICAL VS HYDRAULIC STAMPING PRESSES¹

	Mechanical Press	Hydraulic Press
1. Availability	Readily available in metal stamping shops. Common in automotive industry, with bed size up to 12 ft by 4 ft and pressures to 5,000 tons.	Readily available in plastics compression molding shops with pressures up to 5,000 tons.
2. Stamping pressure:		
a. Press closing rate	Fast to extremely rapid	Slow to very fast
b. Rate of pressure rise	Extremely rapid	Slow to very fast
c. Rate of pressure drop-off	Fast	None (except for leakage)
d. Pressure readout	Not normally available (can add strain gage)	Pressure gage; standard
3. Bottom dead center (bdc) stop	Simple modification must be made.	Inherently present
4. Sensitivity to charge weight	bdc position must be set to fit weight. Overweight can jam and damage press. Underweight results in no pressure on part.	Not affected by weight provided charge volume is at least equal to mold volume.

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The press must be slightly altered to permit the appropriate dwell time at the bottom dead center (bdc) of the stroke. This assures complete rigidizing of the material in the mold.

When the press reaches bdc, the clutch must disengage the flywheel to remove the source of power. The brake then engages, holding the press ram stationary in the bdc position. Since the material shrinks in the thickness direction upon cooling, the pressure is reduced thus permitting the press ram to restock readily without excessive clutch wear on the flywheel face. Brake wear is also minimized since the plastic material acts as a shock absorber as it is contacted by the plunger.

An advantage of a hydraulic press lies in the fact that a conversion from metal stamping is not needed. A hydraulic is always at "bottom dead center" irrespective of the charge or part thickness. Neither the advantages nor the shortcomings of either type of press are so overriding as to eliminate one or another from consideration for any part application. Press availability will probably be the greatest determining factor affecting the sheet processor. Typical molding pressures are in the 1000-3000 psi range. Presses used vary in size from about 75-2,000 tons. A ram travel of 600 in. per min is desirable²⁰.

Cycle times are quite fast, ranging from about 10-30 s, depending on part size and the material selected.

4.4 THERMOFORMING

4.4.1 DEFINITION

Thermoforming (also known as sheet forming, or vacuum forming) is a technique in which the GRTP sheet is heated until it is softened and then formed, using a mold and low pressure.

Basically, the process is very simple. The sheet is either clamped or framed, or held in place some other way, during the heating process which converts the sheet into a soft material that is easily formed by very low pressure—e.g., by atmospheric pressure against a vacuum or slight air pressure. The mold can be either a female cavity or a positive mold. Based on this very simple procedure, many varieties of sheet-forming techniques have been developed to obtain more accurate wall-thickness distribution and the capability of forming deep-drawn articles with uniform distribution of wall thickness.

Figs. 4-24 through 4-28 illustrate some of the methods which have been used successfully with GRTP.

Refer to Fig. 4-24. The plastic sheet is clamped and heated. A vacuum beneath the sheet (A) then causes atmospheric pressure to push the sheet down into the mold. As the plastic contacts the mold (B), it cools. Areas of the sheet reaching the mold last are thinnest (C).

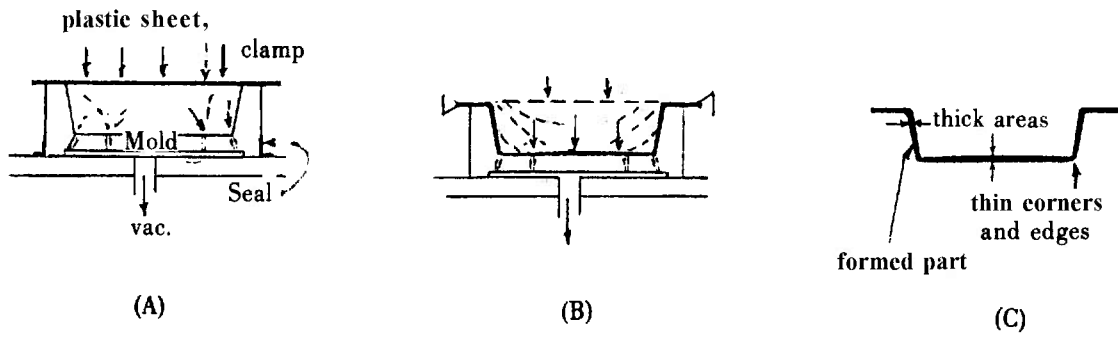


Figure 4-24. Straight Vacuum Forming'

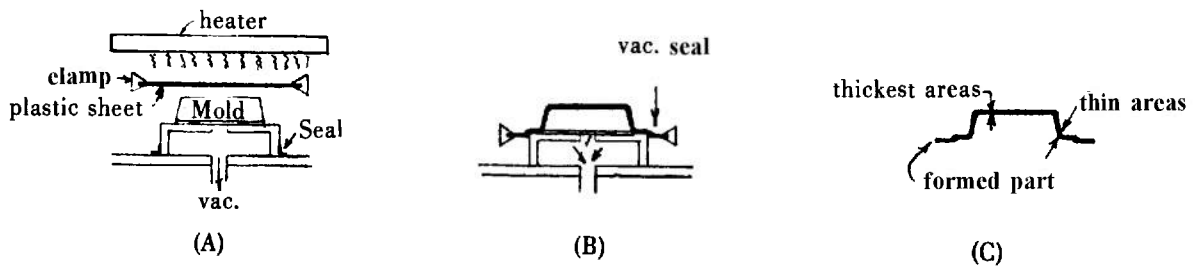


Figure 4-25. Drape Forming'

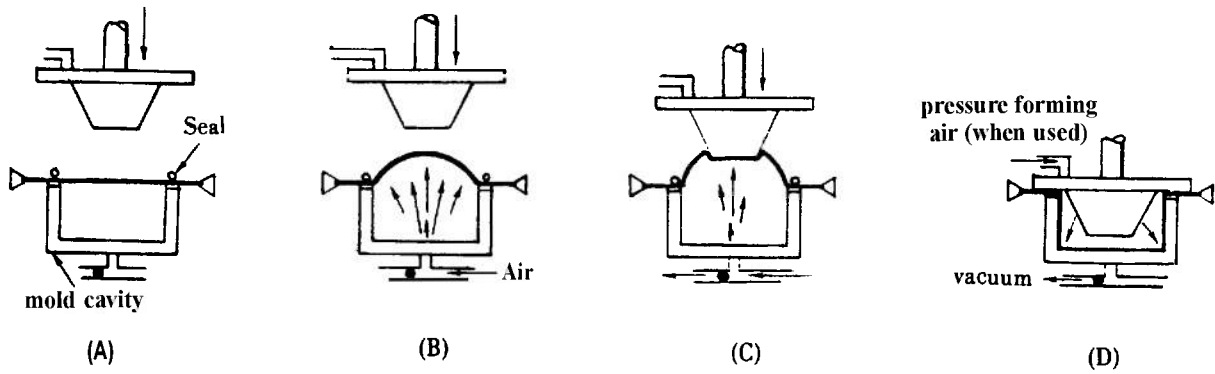


Figure 4-26. Pressure Bubble-Plug Assist Vacuum Forming'

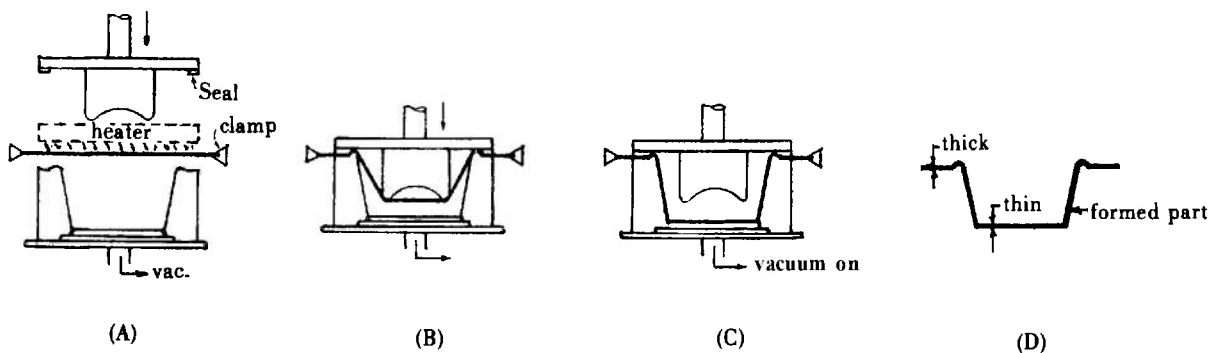
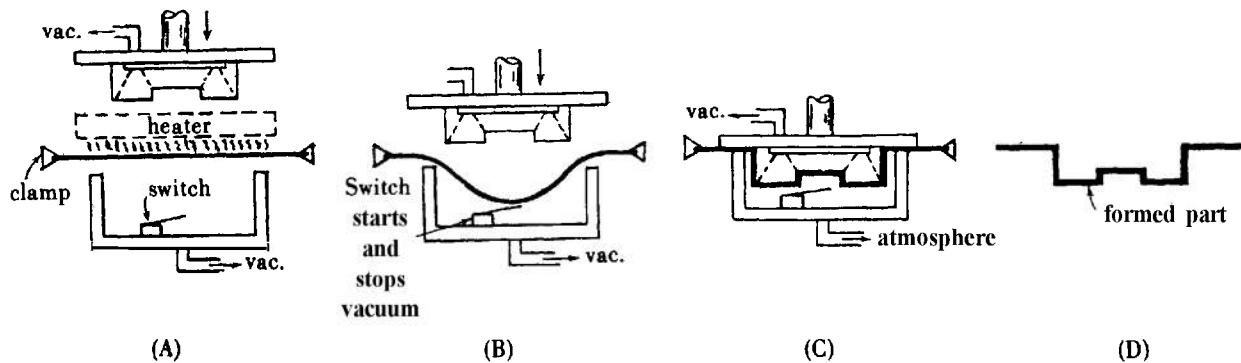


Figure 4-27. Plug Assist Vacuum Forming'

Figure 4-28. Vacuum Snap-Back¹

Refer to Fig. 4-25. The plastic sheet is clamped and heated (A), then drawn over the mold either by pulling it over the mold or by forcing the mold into the sheet. When the mold has been forced into the sheet and a seal created (B), vacuum applied beneath the mold forces the sheet over the male mold. By draping the sheet over the mold, that part of the sheet touching the mold remains close to the original thickness of the sheet. Side walls are formed from the material draped between the top edges of the mold and the bottom seal area at the base. Final wall thickness distribution is shown in the drawing (C)¹.

Refer to Fig. 4-26. After the plastic sheet is heated and sealed across the female cavity (A), air is introduced into the mold cavity and blows the sheet upward into a bubble stretching it evenly (B). Normally an electric photocell is used to control the height of the bubble. A plug, shaped roughly to the contour of the cavity, plunges into the plastic sheet (C). When the plug has reached its lowest position, a vacuum is drawn on the cavity to complete formation of the sheet (D). In some instances pressure forming air is also used in this process.

Refer to Fig. 4-27. After the plastic sheet is heated and sealed across the mold cavity (A) a plug, shaped roughly as the mold cavity but smaller, is plunged into the plastic sheet and pre-stretches the material. When the plug platen has reached its closed position (B), a vacuum is drawn on the mold cavity to complete formation of the sheet. Wall thickness can be varied by changing the shape of the plug (C). Areas of the plug touching the sheet first create thicker areas due to the chilling effect (D). Consequently, plug design is a most important factor in determining just what the geometry of the formed part being produced

by this technique will look like.

Refer to Fig. 4-28. After the plastic sheet is heated and sealed over the top of the female vacuum box (A), a vacuum applied at the bottom of the vacuum box pulls the plastic material into a concave shape. The latter can be controlled by turning the vacuum on and off to maintain a constant shape in the sheet. When the plastic has been prestretched, the male plug enters the sheet (B) and a vacuum is drawn through the male plug. Vacuum beneath the sheet is vented to the atmosphere or light air pressure is applied in place of the vacuum (C). External deep draws (D) can be obtained from the vacuum snap-back process for forming items like luggage, auto parts, etc.

4-4.2 MATERIALS

Extruded glass-reinforced sheet currently is being developed for thermoforming. To date, most work has been done with high density polyethylene which is available commercially from Fiberglass Canada Limited. Other materials being tested are nylon, ABS, polystyrene, polypropylene, and high molecular weight polyethylene. Glass reinforcement has ranged from 10-30%. The strength, stiffness, and heat distortion temperature increased with additional glass and the impact strength decreased—changes in physical properties to be expected with glass fiber reinforcement.

Due to the nature of the extrusion process, there is some fiber alignment on the surface of the extruded sheet. This alignment is believed to be caused by shear effects in the die of the extruder. The net result is sheet with a core of randomly oriented fibers in the plane of the sheet and an upper lower skin of fibers oriented in the

extrusion direction. Table 4-5 shows the effect of this orientation on the mechanical properties of two thicknesses of high density polyethylene (HDPE) reinforced with 20% glass²².

The directional properties of fiber-reinforced sheet are influenced by the sheet thickness and the viscosity of the melt as it passes through the extruder die. As the sheet thickness is increased, the directional properties converge since the oriented surface layers become a smaller portion of the total thickness. When the glass fiber content is increased, the viscosity of the melt increases and, consequently, the thickness of the oriented skins will increase. Table 4-6 shows the change in directional properties as the glass content is increased.

4-4.3 PROCESSING PARAMETERS

Since reinforced thermoplastic sheet has only recently been introduced as a suitable material for thermoforming techniques, little specific processing data have been published. However, from the thermoforming trials conducted to date, only slight variances in the forming characteristics between reinforced and nonreinforced sheet have been noted²³. The slight differences in the glass-reinforced processing parameters can be attributed to the superior thermal and mechanical properties of glass-reinforced sheet over its unreinforced counterpart.

TABLE 4-5. EFFECT OF FIBER ORIENTATION IN THE SURFACE SKINS OF 20% GLASS-REINFORCED SHEET²²

	Sheet Thickness, in. (mm)	
	0.100 (2.5)	0.150 (3.8)
Flexural Strength, × 10 ³ psi —L (MPa) —W	6.74 (46.47)	7.63 (52.61)
	3.63 (25.03)	5.18 (35.71)
Tensile Strength, × 10 ³ psi —L (MPa) —W	5.58 (38.47)	5.55 (38.27)
	5.11 (35.23)	5.28 (36.40)
Flexural Modulus, × 10 ⁶ psi —L (× 10 ² MPa) —W	0.55 (37.92)	0.53 (36.54)
	0.30 (20.68)	0.32 (22.06)
Tensile Modulus, × 10 ⁶ psi —L (× 10 ² MPa) —W	0.50 (34.47)	0.49 (33.78)
	0.40 (27.58)	0.48 (33.09)

NOTE: L = Extrusion Direction
W = Across the sheet

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The increased modulus of reinforced sheet will permit reduced sheet thickness over the unreinforced material. For example, under similar loading conditions, a 220-mil HDPE sheet was found to deflect the same amount as a 187-mil sheet reinforced with 10% glass fiber. Also, the total load carrying capacity of the thinner reinforced sheet was about 35% higher. This permits a 24% reduction in the resin requirement²³.

The following theoretical equation is considered to be quite accurate in predicting heating times for thermoforming²³:

$$\theta = \frac{a^2 (I + 2)}{6\alpha (I - 1)}, s \tag{4-2}$$

where

- a = sheet thickness for single heater, cm
- a = half of sheet thickness for sandwich heaters, cm
- α = thermal diffusivity $k/(c\rho)$, cm²/s
- k = thermal conductivity, W/cm • °C
- c = specific heat, J/g • °C
- ρ = density, g/cm³
- I = temperature uniformity index (temperatures expressed in °C), dimensionless.

I is the ratio of the temperature on the hot surface to that on the cold surface in the case of one side heating. For sandwich heating it is the ratio of the surface temperature to the core temperature. In either case it is a decision that must be made by the thermoformer until enough material data are generated to evaluate its significance. For polyethylene sheet a temperature range through the thickness between 127°C (260°F) and 141°C (286°F) is reasonable and gives an I of 1.1 (Ref. 23).

An infrared heater emits some radiant energy beyond the limits of infrared but a large proportion of its energy is concentrated around a specific wavelength. This can be determined by the surface temperature of the infrared generator. The temperature of most infrared ovens can be controlled, and therefore, the wavelength of the energy emitted can be adjusted to suit the absorption characteristics of materials being heated. By increasing the temperature of the infrared generators, it is highly possible that the amount of emitted energy absorbed by the material will be increased, but the percentage of energy absorbed will decrease. Therefore, any decrease in heating time obtained by operating at higher temperatures is at the expense of the overall efficiency of energy use.

TABLE 4-6. DIRECTIONAL PROPERTIES OF SHEET WITH VARIOUS LEVELS OF GLASS REINFORCEMENT²²

	Glass, %		
	10	20	30
Sheet Thickness, in. (mm)	0.150 (3.8)	0.150 (3.8)	0.150 (3.8)
Flexural Strength, x 10 ³ psi (MPa)	- L	4.51 (31.09)	7.63 (52.61)
	- W	4.07 (28.06)	5.18 (35.71)
Flexural Modulus, x 10 ⁶ psi (x 10 ² MPa)	- L	0.19 (13.10)	0.53 (36.54)
	- W	0.28(19.31)	0.32(22.06)

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The heat energy E put into the sheet to bring it up to forming temperature can be calculated by the following equation²³:

$$E = c\rho t\Delta T, J/cm^2 \quad (4-3)$$

where

- t = sheet thickness, cm
- ΔT = temperature change, (forming temperature - room temperature), deg C.

For 220-mil HDPE sheet this energy E is 149 J/cm², and for 187-mil reinforced sheet the energy is 127 J/cm² giving a 15% reduction in energy requirements. The heating times using sandwich heaters were 192 and 132 s, respectively. This is a 31% reduction in heating time for the reinforced sheet.

The heating time and the energy absorbed by the sheet are used to determine an optimum watt density. The emission efficiency of infrared generators varies with the design but an average value is estimated at about 75%. The directional efficiency also varies but again the average could be around 75%. Therefore, only 56% (0.75²) of the heater rated output is actually incident on the sheet being heated. Since only a percentage of the incident radiation is absorbed, the sheet actually uses only a portion of the rated output of the infrared generator.

In the case of HDPE, only 45% of the incident radiation is absorbed and the sheet actually uses only 25% (0.56 x 0.45) of the rated output of the heater. Therefore, a 220-mil unreinforced HDPE sheet and a 187-mil reinforced sheet require heaters with a rated output of 3 W/cm² and 3.8 W/cm², respectively²³.

4-4.4 EQUIPMENT

4-4.4.1 Thermoforming Machines

Thermoforming equipment consists of:

1. An infrared heater to bring the sheet to the forming temperature.
2. A mold-mounting table with a clamping frame above it to hold the sheet. Both the mold-mounting table and the clamping frame should move in both up and down directions.
3. Vacuum or air pressure equipment.
4. A surge tank which can quickly evacuate the mold in order to draw the sheet into or over the mold.

These basic units—i.e., heater, mold-mounting table, sheet-clamping frame, and vacuum or pressure sources—are contained in every piece of thermoforming equipment; however, for high-speed continuous production, many improvements have been made.

Equipment differs with sheet thickness. There are generally three groups of machines—the general-purpose for drape and vacuum forming; the sheet-fed machine which is usually a shuttle or rotary type, and the roll-fed machine for thin sheet (0.07 in.). It is doubtful if the roll-type machine would be used with reinforced thermoplastics.

High-speed machines for forming heavy sheet are generally three- or four-stage rotary. These machines feature greater speed, and require only one operator and one mold. These rotary machines can also be equipped with automatic loading and unloading equipment, hence little additional labor is required.

Trimming the thermoformed part is an impor-

tant operation because, if it is not tooled properly, the operation can be time-consuming. Also, the amount of scrap generated in the trimming operation can determine the economics of thermoforming processes. If the object to be formed happens to be round, generally the trim scrap will amount to approximately 35% and, in many cases, even higher; therefore, the trim is a critical factor in the cost of the thermoformed object.

Trimming of continuously formed, small, thin objects usually is done in-line or directly in the forming machine. Trimming heavier pieces formed in a rotary or single-table forming machine must always be a separate operation. This is done in a die cutting press by sawing, routing, or punching.

4-4.4.2 Tooling

Molds for prototypes or short runs can be made of wood, plaster, or plastics. These type molds usually require the use of blowers or fans for cooling. Temperature controlled aluminum molds are usually used in mass production. Most metal molds are cast. Coiled metal tubing inside the cast serves as coring for the coolant. A uniform mold surface temperature is necessary for optimum part quality. One problem in the manufacture of molds for thermoforming is the necessity for air channels to apply the vacuum or remove trapped air. Vacuum holes must be numerous and extremely small to remove a large volume of air but not produce imperfections in the finished part. Fine holes have been produced by removing wire embedded in the mold material during casting.

4-4.5 MATERIALS HANDLING

Some sort of handling equipment is required to transfer the sheet from receiving, storage, and to and from the thermoforming machine. The sheets can be stacked on pallets and moved with forklifts and conveyors, vibrated, slid, pushed, and vacuum picked.

4-4.6 ADVANTAGES AND DISADVANTAGES

4-4.6.1 Advantages

Thermoforming has the following advantages over other fabricating techniques:

1. Objects of large area can be created without

high equipment and tooling costs.

2. Molds can be prepared very quickly, reducing lead time for a new item.

3. Sheets of different thickness and stiffness can be molded on the same equipment with only a few changes in heating and cooling.

4. Flat sheets can be predecorated before molding.

5. Thermoformed parts contain no weld lines.

6. Relatively thin-walled objects can be formed.

4-4.6.2 Disadvantages

The following are pertinent disadvantages:

1. Parts generally have to be trimmed after removal from the machine.

2. Close tolerances cannot be held on wall thickness, which means a comparative nonuniform section thickness.

3. Making glossy parts is more of a problem in thermoforming than in injection molding.

4. The resin/glass system has to be extruded first into sheet material which increases the cost of the thermoformed part.

4-5 EXTRUSION

4-5.1 DEFINITION

Extrusion is the process by which glass-reinforced pellets (alone or in combination with unreinforced pellets) or resin powder and glass are fed into a barrel, heated to plasticity, mixed, and forced to flow in a more or less continuous manner through a forming die which is shaped to produce the required cross section. It is employed to produce sheet, rod, tubes, pipes, and other profiles.

The process entails:

1. Material preconditioning and/or compounding

2. Material feeding and metering

3. Barrel heating and cooling

4. Plasticating and mixing

5. Drive mechanisms

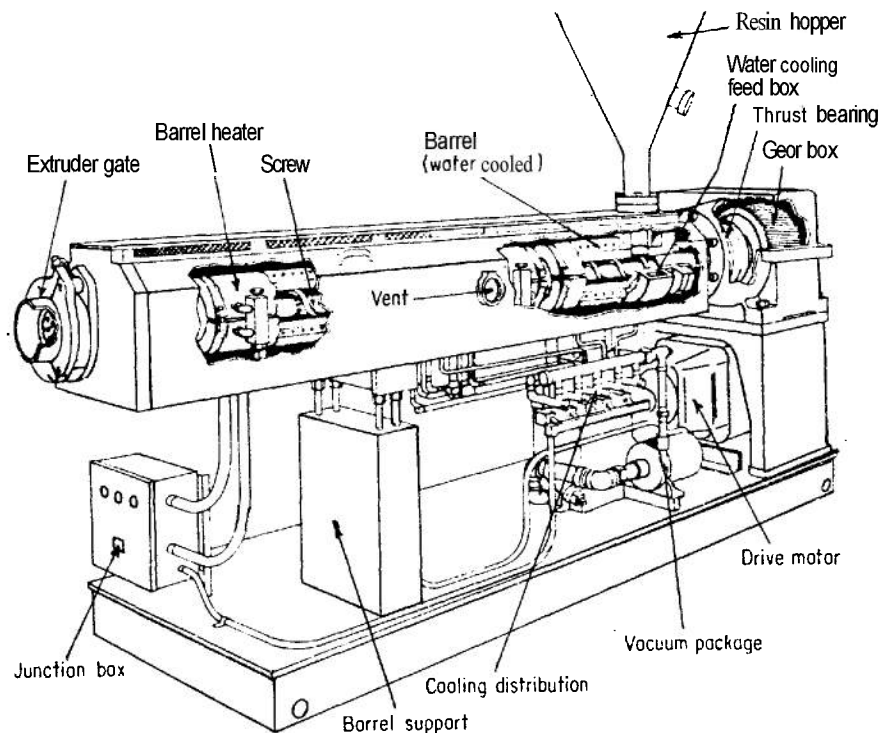
6. Die forming

7. External cooling

8. Takeoff and handling of formed material.

The machine in which the forming process takes place is called an extruder (see Fig. 29).

Extrusion in the glass-reinforced industry is centered primarily around extrusion of glass-reinforced pellets by material suppliers for molding



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Figure 4-29. Line Drawing of a Typical Extrusion Machine²⁴

and sheet forming for stamping and thermoforming operations. As of this writing there is little market for extruded GRTP pipe or other profiles.

4-5.2 MATERIALS

All GRTP can be extruded. Processing parameters will vary with resin system, percent glass filler, extrusion equipment, and part design. The suggested processing parameters for polyacetal are presented in Table 4-7.

4-5.3 EQUIPMENT

4-5.3.1 Dryers

Hygroscopic materials must be dried in a dehumidifying oven or hopper before extruding. Generally, the same type of dryer as used for injection molding is satisfactory.

4-5.3.2 Extruder

The main components of an extruder are mixing and plasticizing devices (screw), barrel, gear box and drive train, instrumentation, and heat-

ing/cooling. These are illustrated in Fig. 4-30. Extruders are specified by two parameters: (1) the inside diameters of the barrel, e.g., 1.75, 2.75, 3.75, 4.5 in., . . .; and (2) by the L/D ratio. This is the ratio of the barrel length to its diameter, for example 20:1, 24:1, 32:1. Generally, GRTP are processed on equipment having a L/D ratio of 20:1 or greater. Units are commercially available in sizes from 2.5-8 in. diameter screws on 36:1 L/D models for reinforced plastics.

There are many variations in extruding machines most of which are in the shear and mixing devices. For the purpose of this handbook only the most popular single, fixed position screw-type extruder will be discussed.

4-5.3.2.1 Barrel

Extruders should be fitted with a nitrided steel or X-alloy lined barrel.

4-5.3.2.2 Screw Design

The selection of screw and barrel is important since these items directly influence the quality of

TABLE 4-7. SUGGESTED EXTRUSION CONDITIONS FOR GLASS-REINFORCED ACETAL**

Condition	Values
Material system	Acetal Celcon GC 25
Extruder	20:1 L/D , 1.75 in.
Screw	PE type (normal) 3:1 compression ratio
Cylinder temperature	350°F rear, 390°F center, 400°F front
Adapter	375°F
Die	390°-400°F
Screw	60, rpm
Cooling	Chill rolls, 150°F top, 200°F center, 200°F bottom

the extrudate. Design factors such as screw profile, compression ratio, and clearance between screw and barrel must be considered. The screw length is expressed in relation to its diameter. A screw L/D ratio of at least 20:1 is suggested. This permits progressive heating and fusion of the material without localized overheating.

The screw has three zones—the feed, compression (or transition), and metering. The feed zone picks up the material from the hopper and feeds it at a pressure sufficient to assure proper functioning of the compression zone. Feed zone conveying is optimized by a deep screw channel and a helix angle appropriate for the coefficient of friction between the polymer and screw. A helix angle of 17.7 deg has been used for many plastics. The channel depth of the feed zone may be approximately three times that of the metering zone²⁶.

The compression zone converts the material to a dense melt of uniform temperature and viscosity for delivery to the metering zone. The relationship between the channel depth of the feed zone to the metering zone is termed the compression ratio. Screw compression ratios of at least 3:1 usually are recommended. This is accomplished by a gradual decrease in the channel depth along this section of the screw. Normally, the minimum channel depth of the compression zone equals the uniform channel depth of the metering zone to which it is joined. The compression zone should be tailored to the bulk density and melting characteristics of the material so that the occluded air can be pushed back through the feed zone as the material is melted. Numerous screw designs have been invented to improve mixing and provide a more homogeneous melt. Each extruder manufacturer has his own suggestions for improving the mixing of his extruders with each resin system.

The metering zone provides the extruder head with plastic melt at constant flow rate and pressure. Ideally, all of the pressure buildup along the

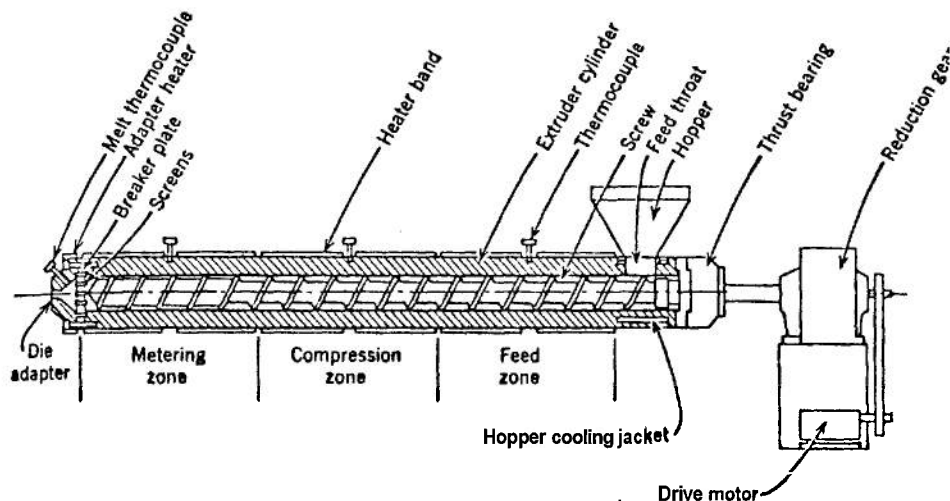


Figure 4-30. Typical Single-Stage, Single-Screw Extruder for Plastics²⁶

length of the screw should occur within this zone. However, a uniform melt viscosity and zero pressure is all that is required for this zone to function in a satisfactory manner. As a result of the shallow channel depth in this zone, the shear rates are higher and the mixing more intense.

Mathematical models have been developed for models of the three zones of the screw to predict temperature, pressure, and melt channel geometry of the materials being processed as a function of extruder design and operating conditions.

4-5.3.2.3 Drive Train

The extruder drive train (motor and gear box) must be able to provide initial start-up torque and maintain the horsepower required to deliver the required output. The dc drives are preferred because of their accurate speed control and efficiency. They also provide constant torque over a wide range of operating speeds.

Drive motors usually are connected to the gear reducer by belts or a flexible coupling. The appropriate drive power and gear box combination is critical in order to achieve optimum results.²⁴

Equipment manufacturers have related horsepower to extruder diameter. Excessive horsepower is costly initially, and more expensive to operate and maintain.

Gear boxes with at least a 1.25 service factor are recommended. However, the final decision will depend upon the horsepower and application needs²⁴.

4-5.3.2.4 Thrust Bearing

Thrust bearings absorb the back force generated by the screw as it pressurizes the die. The life of a thrust bearing is described in hours termed B10 life. The B10 life hours is the minimum time normally that the bearing will survive; it is defined as the time (hours) that 10% of the bearings fail at a specified psi and rpm. The average life is about five times the B10 hours. The B10 life is inversely proportional to rpm—i.e., if the rpm is reduced by half, the B10 life will be doubled. The bearing psi is exponentially related to the B10 life hours by a power of 3.3. As an example, if a bearing with a B10 rating of 136,000 h is operated at 5000 psi and 100 rpm, reducing only the psi to 2500 will increase the B10 life to 1,339,000 h.

4-5.3.2.5 Breaker Plates, Valving, and Extrusion Dies

The breaker plate is positioned between the output end of the barrel and the head of the extruder. It usually is made from one or two steel plates drilled with a number of holes. Screen-packs are placed between the two plates (or where there is only one plate, between the plate and the screw). The thickness of the plates and screens should be adequate to slow down or stop the helical movement of the material initiated by the rotation of the screw. The size of the breaker plate holes and the screenpack mesh must be optimized for optimum flow and pressure. Also the distance between the end of the screw and first plate or screw is important to eliminate irregular flow through the screenplate and prevent excessive heating times.

The extrusion die shapes the extrudate so that after extrudate swell, shrinkage, and drawdown, the product will meet the size and shape requirements. The shapes of most dies must be adjustable since the swelling behavior of the extrudate is not precisely known and can vary in a given cross section. The dies also help to control the rate and uniformity of polymer flow. This is accomplished by the geometrical die resistance and control of die temperature.

Extrusion dies usually are made from alloy steel, finished to a few microinches, plated, and buffed. Hard chrome plating is used for most materials except corrosive resins such as vinyls where nickel is used. Temperature control to within 2-3 deg F is required at specific zones in the die. Proportioning temperature controllers with sensing elements deep in the die body provide excellent temperature control in electrical heating systems. In some applications, portions of the die may be cooled rather than heated for internal sizing and support of the extrudate.

Pressure valves are used to increase or decrease back pressure and thus control pressure at the extruder head. Pressure valves can provide good pressure control and remove this function from die design and screen-pack arrangement. Two types of pressure valves are available, internal and external.

The internal pressure valve is a movable screw which can be adjusted forward or backward to increase or decrease pressure. Moving the screw varies the size of the opening between the end of

the screw and the breaker plate and adapter. External pressure valves make use of some type of pin arrangement which varies the size of the opening at the extruder adapter, thereby varying pressure.

4-5.3.2.6 Heating and Cooling

The most common methods for heating and cooling the barrels are electrical heating and air or water cooling. The barrel usually is divided into at least three temperature controlled zones, which permit better heating control.

The first zone, at the feed hopper, should be water-cooled. The circulation of cold water around the barrel regulates the melting and reduces the risk of irregularity in the output of molten material from the die.

An extra heater band or an insulator should cover the collar which fixes the head to the barrel. Thermal insulation at this point is of paramount importance because it corresponds to the position of the breaker plate and screenpacks (i.e., where maximum pressure occurs). Finally, the head and the die should each have their own separate heating and control systems.

There are at least eight temperature controlled zones, namely:

- a. 1 cooled zone at the hopper
- b. 3 zones along the barrel
- c. 1 heated or insulated zone on the collar which fixes the head (as required)
- d. 2 zones on the head
- e. 1 zone on the die.

Normally, the temperature profile adopted rises along the barrel to a maximum at the breaker plate and then decreases toward the die.

Electrical heaters must fit the barrel properly. Failure to have a solid surface-to-surface contact will cause uneven heating, hot spots in the heater, and premature heater failure. The heater should have provision for adjustment after heat up to maintain proper fit. It should be able to expand and contract without exerting undue strain on the elements. Heaters should also have an adequate kilowatt rating to insure good heater life and improve the operating cost efficiency.

When a liquid system is used, it should be the closed-loop type, with each zone on separate instruments for more accurate control. The closed-loop system uses treated water to reduce the possibility of contamination. Plant water is passed

through a heat exchanger to provide the cooling for the closed-loop system. A modulating valve is recommended on the plant water side to provide the required amount of cooling water to the heat exchanger.²⁴

Air cooling should meet the requirements of each zone area. Oversizing the cooling fans will not improve the capability to remove heat; more important is the direction of the air flow. Direction is essential for efficient cooling to maintain a balanced air flow. A well designed system will include the use of baffles to direct the air flow.

4-5.3.2.7 Instrumentation

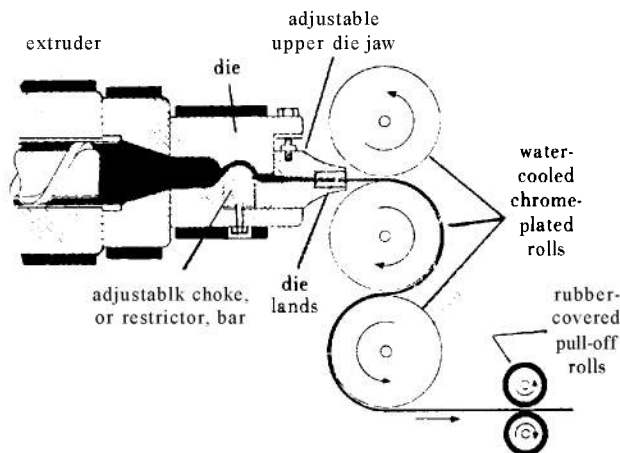
The extruder barrel zone instruments are essential in controlling the performance of the feed screw with respect to output and quality of the extrudate. A three-position instrument to minimize radical zone temperature variations usually is preferred. Sophisticated mixing screws now demand control on both heating and cooling, especially with the use of a liquid cooling system. It is advisable initially to equip the extruder with proportioning controls for both the heating and cooling systems. An extruder zone temperature control system is highly dependent on the thermocouple response. A poorly located thermocouple and improper immersion depth will limit the ability of the instrument to sense and control the heating zone variations accurately. The control system should maintain a set point of ± 2.5 deg F or better²⁴.

4-5.4 MATERIALS HANDLING AND AUXILIARY EQUIPMENT

The design of auxiliary and handling equipment will depend upon the end product. Generally, extrusion of glass-reinforced materials has been limited to a few profiles and sheeting. Typical equipment consists of calibration and sizing, cooling, takeoff, cooling, and cutting.

Fig. 4-31 shows the cross section die and takeoff unit for extruding sheeting.

The takeoff unit for sheeting usually consists of a vertical stack of three driven, highly polished, chrome-plated rolls and a pair of driven, rubber-covered pull-off rolls. The chrome-plated rolls serve three purposes — cooling, gage control, and imparting a desired finish to the sheet. The cooling rolls are generally of twin-shell construction



Courtesy of U.S. Industrial Chemicals Company.

Figure 4-31. Cross Section of a Sheeting Die and Takeoff Unit for **Sheeting**²⁷

to permit close temperature control of the surface. The coolant is usually water of closely controlled temperature. The diameter of the rolls depends on the linear speed of the sheet and the amount of cooling required. The rubber rolls serve for tension control and as a pull-off device.

The spacing between the top and middle rolls should be less than the desired thickness of the finished sheet. The spacing between the middle and bottom rolls should be more than this thickness. The spacing between the rubber rolls should be at a minimum to maintain a uniform pull on the sheet.

The variable-speed drive for the takeoff unit should have very uniform speed. It must be easy to adjust to permit making small changes in speed. Also the framework for the takeoff unit must be relatively free of vibration. Even slight vibrations may cause a wavy appearance of the sheet and pulsating variations in the gage.

Sheet should be cut to the desired length and stacked flat. Usually, a traveling power shear cuts the sheet automatically to the desired lengths. Roll temperatures have a decisive influence on the quality of the finished sheet. If the rolls are too hot, the sheet will not be cooled sufficiently for easy handling and will tend to curl in the transverse direction. If the rolls are too cold, the sheet will curl in the machine direction, resulting in a pitted surface²⁴.

4-5.5 ADVANTAGES AND DISADVANTAGES

The major disadvantage in extruding GRTP is the limitation in complex designs and glass fiber orientation. An advantage is that it presents an economical process for preparing sheet and billets for stamping and thermoforming.

4-6 ROTATIONAL MOLDING

4-6.1 DEFINITION

Rotational molding, rotomolding, or rotocasting is a production process to form hollow parts of limitless size wherein powdered resin and glass fibers are charged into a split mold. The mold is then continuously rotated in a biaxial mode, in a high-temperature environment to above the resin melt temperature. When the plastic material has covered the inside of the mold and densified, the mold assembly while still rotating is cooled to room temperature. The rotation is stopped and the part removed.

4-6.2 MATERIALS

Generally a -35 mesh thermoplastic resin powder and 1/8 in. long fiberglass reinforcement are used.

4-6.3 PROCESS, EQUIPMENT AND TOOLING, AND APPLICATIONS

The whole field of rotational molding is covered in the Army Engineering Design Handbook, AMCP 706-312 *Rotational Molding of Plastic Powders*. Those interested should refer to this handbook for details concerning equipment, molds, processing parameters, quality control, part design, materials advantages and disadvantages of the process, economics, and pertinent applications.

4-7 MACHINING

4-7.1 INTRODUCTION

Fiberglass reinforced thermoplastics can be machined satisfactorily with proper methods and tools. However, it should be recognized that they are far different from metallic materials. In fact each type of reinforced plastic has its own unique

properties (see Chapter 3) and will have different machining characteristics.

For best results only sharp tools should be used to provide adequate chip clearance. Also, the work must be supported properly.

Less rake and greater clearance on the cutting tools are required because of the greater resiliency of these materials over metals. High speeds and feeds can be obtained because of the lower shear strength of the materials.

Poor tolerance control, poor finish, and gumming will not be as great a problem as that for unreinforced materials because of the higher melting points of glass-reinforced materials. Adequate cutting tool clearance is necessary to avoid rubbing and frictional heat which can make the materials somewhat difficult to handle. To assist in dissipating heat, a water mist spray or air jet should be used at the point of contact.

No single machining parameter is satisfactory for all thermoplastics, but the recommendations that follow should serve as a starting point and guide to assist operators in determining their own optimum operating conditions.

4-7.2 DRILLING

Tools should be kept extremely sharp. Drill points must be sharpened frequently with care to avoid loss of the desired point angle. Carbide-tipped points are recommended since they hold a good cutting edge and may be used at high speeds.

While drilling, an air blast may be used to assist in clearing chips and preventing overheating, which could cause clogging. The air blast method is only recommended when there is a suction pickup of the chips and dust. A liquid lubricant or cooling agent is suggested to control dust problems. The liquid can be made up from a 10% water soluble oil and water, or soapy water.

The speeds used in drilling will depend on size and depth of the holes. In general, speeds are decreased with an increase in the size of the hole and increased with the hardness of the material. Drill speed should be as fast as possible without causing melting or gumming. For example, drill speeds of 1000-3000 rpm have been used successfully for 30% glass-reinforced polyester. Pressure should be relaxed near the termination of through holes to prevent breakthrough.

Drills with two wide slow helical and highly polished or chrome-plated flutes are recom-

mended to facilitate the removal of the chips with minimum friction. The wide flutes also provide an easy entrance for the cutting fluid. Also, all tool surfaces in contact with the plastic composite should be honed or polished to reduce frictional heat. To help remove chips and allow the drill to cool, the drill should be backed out of the hole frequently (about every 1/4 in. of depth), especially in blind holes. Compared to metals, much less power is needed to drill these materials because of their lower shear strength²⁸.

Drills should be 0.002-0.004 in. oversize to compensate for material yield. A drill one size larger is suggested if drilling is preliminary to tapping. Drills designed especially for plastics are available commercially and can be used with reinforced plastics²⁸.

4-7.3 SAWING

GRTP may be sawed with almost any type of saw such as circular or band.

4-7.3.1 Circular Sawing

Circular saws should be hollow-ground with all burrs removed by stoning. Frequent sharpening is required. A jet of air directed at the cutting area will disperse the chips and cool the blade when sawing thin sections. A water spray should be used for thicker sections (1/2 in. or more) for cooling and a cleaner cut.

The circular blades are usually 1/32-1/8 in. thick with the thinner blades being used when cutting pieces 0.050-0.100 in. thick. There can be 6 to 12 teeth per inch, depending on the thickness of the composite to be cut²⁸.

Care must be used not to force the cut, thereby distorting the wheel. Idling, however, can create friction and heat which causes excessive dulling. Attempting to force the cut also results in heating the blade and gumming of the material. The saw teeth will also load up and cause a rough cut.

Carbide blades are not generally recommended due to wear, but carbide abrasive wheels can be used. The abrasive wheels will produce an equally good finish on the cut surface at a considerable increase in tool life. Resin-bonded saws are satisfactory and notching the wheel helps to promote self-cleaning²⁸.

4-7.3.2 Band Sawing

Band saws are more superior than circular

saws for cutting GRTP because they run cooler. There should be enough set in the blade to give adequate clearance. It is suggested that one-half the thickness of the blade on each side be used so that saws give a width of cut double their thickness.

The proper rate of feed is important. Most sawing operations are hand-fed, and rate of feed must be learned from experience. Attempts to force the feed will result in heating the blade, gumming the material, and a rough cut. It is always best to relieve the feed pressure near the end of the cut to avoid chipping.

An air jet can be used at the point of contact with a vacuum pickup to remove the dust. A preferred method of removing the dust is spraying a 10% water soluble oil solution or a soapy water solution at the point of contact. This will also aid in keeping both the part and the tool cool.

Since a slow feed uses only the tips of the cutting edges, which in turn diminishes the blade life, the feed should be as fast as possible without distorting the blade.

Skip-tooth or buttress blades with 2-6 teeth, hardened on the tooth edge but just soft enough to be filed, should be used. Blades must be kept sharp²⁸.

4-7.4 TURNING

High-speed steel may be used for cutting tools, but carbide-tipped or diamond tools are best for long production runs since they hold a sharper edge for a longer time. The cutting edges of the tools should be kept honed, and the top surface should be lapped to a bright finish.

Lubricating of the turning tool is not necessary and sometimes not permissible. In either case, a carbide-tipped or diamond-tipped tool will increase production and tool life. Dust and shavings should be removed by an efficient dust collection system.

If lubrication can be used or is desired, a mist spray of a mixture of equal parts of soluble oil and water or a soap solution at the point of contact will give good results.

Surface speeds range from 400-700 rpm with feeds from 0.001-0.025 in., but this is determined largely by the kind of tool used and desired finish. It is suggested to have a 10-20 deg clearance with a 0-5 deg positive rake. Standard lathes and screw machines can be used for this type of operation.

Clean, smooth surfaces can be obtained at rapid speeds. The speed and feed must be determined largely by the type of base resin, the finish desired, and the kind of tool used²⁸.

4-7.5 CUTOFF AND FACE MILLING

Front and side clearances should be somewhat greater than those of standard turning tools. The tools should be honed or polished to reduce frictional drag where they contact the workpiece.

Similar methods used for brass or mild steel can be used when turning, boring, facing, or grooving. Cuts can range from 0.005-0.025 in.

Multiple cutting edges are usually found on milling cutters. Too low a table travel will generate excessive heat, and too high a table travel will cause a rough surface. A happy medium for each machine can be found by trial and error²⁸.

4-7.6 FILING

Best results are obtained when the most coarse file, consistent with the size of the surface and the finish required, is used. Milled curved-tooth files having coarse single-cut or double cut shear-type teeth are particularly suitable. Frequent brushing is recommended to prevent clogging. A rotary file or bur is excellent to remove material rapidly. Ground burs provide better chip clearance than hand cut rotary files and therefore are preferred.

High speed steel ground burs, medium cut, or carbide burs, medium or diamond cut, give satisfactory performance. Steel burs are operated at about 800-1000 surface fpm and carbide at around 2000 fpm. Carbide burs will give much better life and may be more economical for high production rates.

4-7.7 THREADING AND TAPPING

Threads may be cut on a lathe. Most materials may also be threaded with conventional taps and dies. A special tap designed for plastics, which has two flutes and a 6-8 deg rake, offers some advantages in greater chip clearance.

4-7.8 REAMING

Straight-fluted or spiral reamers with polished flutes and narrow margins are suitable. A jet of air should be used as a coolant.

4-8 DECORATING (See also par. 6-13)

Glass reinforcement has little effect on the ability to decorate thermoplastics. The controlling factors in painting, printing, metallizing, plating, hot foil stamping, etc., are the resin system and product design.

In surface cooling, the chemistry must be carefully selected for compatibility with the compound used to ensure good adhesion and prevent the possibility of solvent attack. Most organic surface coatings or paints provide good adhesion to GRTP parts except for polyethylene and polypropylene. Some satisfactory primer and top coat systems for several GRTP parts are given below*:

Resin System	Epoxy	Acrylic	Alkyd	Acrylic Emulsion
ABS	NA	F	G	G
SAN	NA	F	G	G
Polystyrene	NA	F	F	F
Nylon	G	P	NA	NA

G = good, F = fair, P = poor, NA = not applicable.

A primer coat promotes good adhesion of the finish coat. Primer selection should be based on performance requirements. If powder coating is to be used as a finish coat, the primer coat must be conductive. Powder coating is electrostatically applied over the conductive primer coating, then baked to fuse the finish.

A top coat, providing color and luster to the part, must bond well to the primer coat. The top coat may, in some cases, be applied directly to pigmented GRTP parts without priming.

Glass reinforcement permits higher temperature bake cycles in painting than the unreinforced system. Also, the additional shrinkage experienced on parts subjected to paint baking ovens above the normal mold shrinkage allowances is reduced.

Decorations can also be applied to molded surfaces by silk screening, decals, and pressure-sensitive appliques¹.

All GRTP molding materials can be pigmented. Practically any color can be achieved. Pigmentation can be used when color match is not critical. In cases where color match is critical, consideration should be given to painting the surface. The substrate can be pigmented to approximate close-

ly the painted color, so that in-service chipping or scratching of the surface paint will hardly be noticeable.

In vacuum metallizing, the increased mechanical and thermal properties of the reinforced materials allow a reduction in the metal required over that of the nonreinforced material. Also, their increased thermal properties permit faster curing cycles and reduced warpage over unreinforced materials. Since GRTP are not transparent, only first surface vacuum metallizing techniques can be employed. In addition, somewhat higher pigment volume concentrations are required for GRTP but the higher curing temperatures employed reduce cycle times. This results in more complete removal of solvents and vapors which interfere with the pumping cycle and metallizing. For example, the standard base coat cure temperature for glass-reinforced styrenics is 80°C, 14-28 deg C (175°F, 25-50 deg F) higher than the heat distortion of unreinforced resins; temperatures as high as 135°C (275°F) are used for glass-reinforced nylon 6²⁹.

Of the GRTP only ABS, polypropylene, polysulfone, and modified phenylene oxide are electroplated. Of these ABS represents about 85% of the market. Since the introduction of platable plastics, new formulations have been developed to give superior physical properties, platability, and appearance. For example, 25% glass-filled ABS has a shrinkage nearly equal to that of die-cast metals; the increased stiffness reduces distortion during the plating operation; and a reduction of 50% in the coefficient of linear thermal expansion permits it to pass the standard thermal cycling test of 82° to -40°C (190° to -40°F) (Ref. 29).

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CHAPTER 5

BONDING, JOINING, AND FASTENING

The techniques of bonding, joining, and fastening GRTP's are treated briefly. The methods of mechanical fastening, ultrasonic welding, thermal welding, spin welding, solvent bonding, and adhesive bonding are described. Criteria are given for deciding upon the joining mechanism. Limitations imposed by the joining process, the resin system, and the shape/size of the fabricated product are considered. Comparison of bond strengths by various joining techniques are presented.

5-1 INTRODUCTION

The field of bonding, joining, and fastening is very broad and could well be entitled to a handbook of its own. Therefore, for the purpose of this handbook each joining technique will be described briefly to familiarize the reader with the joining options available to him. Further information on joining is given in Chapter 6. As a general rule, GRTP should be treated in a manner similar to the unreinforced material. The matrix material is the determining factor.

Some of the advantages of the glass reinforcement are that the glass provides a rough surface finish, and an increased modulus and coefficient of friction over the nonreinforced material. The disadvantages are that glass fibers are difficult to disperse across the bonded area, and the effects of finishes and coupling agents, if any, are not fully understood.

The following considerations should be reviewed in determining the joining mechanisms:

1. Mechanical fasteners offer ultimate bonding strength immediately.
2. Mechanical fasteners are not subject to chemical change.
3. Mechanical fasteners avoid certain production problems encountered with other joining methods in surface preparation.
4. Mechanical fasteners introduce stress concentration which must be carefully evaluated by the designer.
5. Welding techniques produce a smooth part surface contour, reduced weight, and vibration-damping properties.
6. Crystalline matrix materials are best bonded by heat rather than adhesives. The best adhesive is the molten polymer itself.
7. Crystalline matrix materials melt more sharply than amorphous resins which is advantageous in welding techniques.
8. Amorphous matrix materials are readily

bonded to themselves by solvent bonding.

9. When heated above their melting points, the crystalline matrixes become soluble; these melts may be used to bond the plastics to themselves or other materials through heat alone.

Table 5-1 presents a general guide for selecting joining and fastening methods for GRTP.

5-2 ADHESIVE BONDING

5-2.1 DEFINITION

Adhesive bonding consists of interposing a layer of an adhesive composition chemically different from the plastics to be bonded between the adherends. It is one of the most popular and versatile methods to join plastics. Some of its advantages are uniform distribution of stresses over the assembled areas, a high strength/weight ratio, a simplified means of assembling small or complex-shaped plastic parts, and in some instances thermal or electrical conductivity.

The properties of the adhesive bonded joint depend upon the characteristics of the material, the cohesive strength of the adhesives, and the design of the joint. Unfortunately, there is no one adhesive system which will bond all GRTP materials. Each bonding operation must be reviewed to select the appropriate adhesive for:

1. The matrix system
2. Stresses to which the bonded joint will be subjected
3. Geometry of the joint
4. Environmental elements the joint will encounter
5. Any limitations in heat, pressure, or time required to effect the bond
6. Availability of required equipment used in bonding (presses, ovens, heat lamps, clamps, etc.)
7. Cost and expediency.

Adhesives normally are applied by one of the following methods; brush, flow brushes, dipping, glue guns, rollers, flow rollers, and spray.

TABLE 5-1. JOINING METHODS FOR GRTP's¹

Resin System	Mechanical Fastening	Ultrasonic Welding	Thermal Welding	Spin Welding	Solvent Bonding	Adhesive Bonding
THERMOPLASTICS						
ABS	G	E-G	G	G	G	G
Acetal*	E	G	G	G	P	F
SAN	G	G	G	G	G	G
Nylon	G	G	G	G	P	F
Polycarbonate	G	E	G	G	G	G
Polyethylene*	P	G-P	G	G	P	F-P
Polyphenylene Oxide	G	G	G	E	E-G	G
Polypropylene*	F-P	G-P	G	E	P	F-P
Polystyrene	G-F	E-P	G	E	P	G
Polysulfone	G	E	E	E	G	G

E = excellent

G = good

F = fair

P = poor

NA = not applicable

*When adhesive bonding is used, surface treatment is required.

5-2.2 ADHESIVE BONDING TECHNIQUES

Very little has been published on specific recommendations for adhesive bonding GRTP. When specific recommendations are not available, the reader should query the material supplier or start with the recommendations for the base material.

Best bond strengths normally are obtained on parts when the mating surfaces have been sanded, cleaned, and degreased by wiping with a solvent such as acetone. Good bonds usually require closely mated surfaces; however, some higher viscosity adhesives are sometimes used as gap-fillers.

When cementing plastic parts to metal parts, a room temperature cure is recommended to avoid creating strains in the adhesive caused by the difference in coefficient of thermal expansion. This differential can cause adhesive cracking and decrease the bond strength. Also, curing temperatures must not exceed the heat distortion temperature of the plastic.

5-2.2.1 Polyester (Polybutylene-terephthalate)

One group of adhesives which may be used with PBT (Celanex) reinforced resins are those based

on cyanoacrylate monomers. Such materials are Permabond Blue Label (Rexco Corporation, New York, NY) and Eastman 910 (Eastman Chemical Co., Kingsport, TN). Tensile shear strengths of 400-450 psi can be obtained with these adhesives. They are recommended for environments involving contact with alcohol, benzene, acetone, gasoline, propane, light oil, or similar solvents. High moisture exposures, alkaline materials, and dilute acids may reduce the bond strength. Eastman 910 softens at 165°C (330°F) and Permabond softens at 140°C (284°F). A curing time of 24 h at room temperature is recommended before use².

Epoxy based adhesives also work well with Celanex reinforced resins. Some suggested epoxy adhesives are Scotch-Weld 2214 and 2216, manufactured by the 3M Co., St. Paul, MN. Scotch-Weld 2214 is a one-part epoxy which can be cured in 40 min at 120°C (250°F). Scotch-Weld 2216 is a two-part system which cures in 24 h at room temperature. Both of these adhesives give tensile shear strengths in excess of 500 psi and are resistant to such environments as fuels, salt spray, and air up to 93°C (200°F) continuous and (250°-300°F) short-term. Many other epoxy-based adhesives are also suitable for use with Celanex².

Another method of joining Celanex is with adhesive bonding tape. One such tape, Bostik

10-253, resulted in tensile shear strengths of 480 psi when cured at 135°C (275°F) for 2 h, 600 psi when cured at 150°C (300°F) for 4 h, and 750 psi when cured at 177°C (350°F) for 2 h. This tape is available from the Girder Div., USM Corporation, E. Rutherford, NJ².

5-2.2.2 Polycarbonate

Polycarbonate (Lexan) resin can be cemented using epoxy systems containing room temperature curing hardeners such as diethylene triamine or with systems containing elevated temperature curing hardeners such as anhydrides³.

Epoxy formulations with amine hardeners, cured at room or elevated temperature, have a tendency to become hard and brittle. The addition of polysulphide modifiers increases elasticity, although at the expense of generally lower bond strength. These adhesives permit a fairly thick cement line³.

Amine-cured or polyamide-cured epoxies are not generally recommended for hot water or steam environments above 120°C (250°F).

Anhydride-cured epoxies require a high temperature cure. Before applying epoxy, parts should be predried for 2 to 3 h at 120°C (250°F) in an air-circulating oven to drive out residual moisture. The cure temperature should not exceed 132°C (270°F). RTV silicone adhesives are recommended for applications requiring excellent bond strength, a high service temperature, and good thermal expansion.

For optimum performance the following procedure is recommended³:

1. Lightly abrade mating surfaces with fine emery.
2. Clean surfaces of grease or foreign material with methyl alcohol or other compatible cleaning solutions.
3. Prime abraded surfaces with General Electric silicone primer SS-4004 and allow a minimum of 1-h dry time (unprimed surfaces reduce bond strength significantly).
4. Apply silicone adhesive in desired thickness. Final bond thickness may range from 0.005-0.030 in.
5. Assemble.

Polyurethane adhesives are commonly recommended for bonding Lexan resin to metal, glass, ceramics, fluorocarbons, and other plastics⁵. These two-part adhesives are characterized by bonds which have excellent room temperature

shear and lap strength, high impact resistance, and excellent low temperature performance. However, polyurethane adhesives are generally limited to service temperatures under 93°C (200°F). At temperatures above 93°C (200°F), tensile lap shear values decline dramatically. Also, they suffer from excessive creep at room temperature and may exhibit undesirable changes in properties with aging.

There are a number of one-part adhesive systems recommended for use with Lexan resin. Eastman 910MHT cures at room temperature to a clear film and has the advantage of a wide use temperature range. Some epoxy-polyamide one-part systems and rubber or neoprene-based systems also produce good adhesion³.

Hot melt adhesives, another class of one-part systems, produce excellent adhesion. These adhesives reach their ultimate strength seconds after application but may lose their strength at temperatures below -18°C (0°F) or above 93°C (200°F). Some are also subject to cold flow under prolonged heavy loading. However, their resistance to hot water is excellent³.

5-2.2.3 Polyphenylene Oxide (PPO)

Satisfactory tensile shear stresses may be achieved in the bonding of glass-filled Noryl or PPO parts with a variety of epoxy, rubber-based, or silicone adhesives. Excellent bond strengths of greater than 5,500 psi have been obtained with Allaco M-2 adhesive (Allaco Products). None of the adhesives listed in Table 5-2 show any evidence of attack on glass-filled PPO or Noryl.

TABLE 5-2. TYPICAL ADHESIVE BOND STRENGTHS⁴

Adhesive	Tensile Shear Stress, psi (Lap Joints)	
	Noryl GFN3-111	PPO GF3-111
Allaco M-2 (Allaco Products)	5,500	5,500
Uralane 8089 (Furane Plastics)	2,500	3,100
Uralane 5716 (Furane Plastics)	2,600	2,600
Epon 907 (Shell Chemical)	1,500	1,200

Manufacturers' recommended cure times and temperatures should be followed, bearing in mind that the latter should not be much higher than the heat deflection temperature of the resin being bonded⁴.

5-3 SOLVENT BONDING

5-3.1 DEFINITION

Solvent bonding consists of treating the bond area with a minimum amount of solvent to soften the surface, then clamping the surfaces together to form the joint. In some cases a simple solvent is used; or the solvent may be a catalyzed monomer or it may contain dissolved polymer, the same as the part matrix (dope). This process can be used for the more amorphous and soluble thermoplastics but is not satisfactory for the more crystalline, insoluble matrixes such as polyethylene and fluorocarbons. Dissimilar materials can be solvent cemented provided their matrixes are compatible with each other in solution and in a molten condition.

The selection of the best solvent to use for solvent cementing a given GRTP is determined by consideration of the solubility parameters of the matrix materials. Each material dissolves best in solvents whose solubility parameters are about equal to its own matrix resin. Therefore, the selection of solvents for GRTP would be the same as the unreinforced material.

5-3.2 GENERAL TECHNIQUES

The surfaces to be cemented must be clean and prepared properly (usually lightly sanded). The surfaces should be aligned as nearly perfectly as practicable to avoid large voids. Where the problem of getting proper contact is aggravated by warpage, shrinkage, flash, ejector-pin marks, etc., a void-filling cement such as the polymerizable type should be employed.

Cement should be applied evenly over the entire joint surface, preferably to both adherend surfaces. Care must be taken to prevent application to surfaces other than those to be joined in order to avoid disfigurement of the plastic parts.

The assembly should be made as soon as the surfaces have become tacky; this usually means within a few seconds after application. Enough pressure should be applied to hold the cemented joint until it has hardened to the extent that

there is no movement when released. If the required clamping process actually deforms the parts, the stress due to springback must be relieved before the joint hardens or the joint may subsequently fail. This may be accomplished by releasing the clamps while the adhesive is just slightly "wet".

Care must be taken that the vapor from the solvent is not confined since the vapor and its condensate may etch and craze other areas of the plastic parts. Adequate ventilation is also important in protecting personnel from the toxicity and fire hazards of the solvents employed.

Cements may be applied by a variety of methods such as felt pad, brush, flowing equipment, dip, and spray gun. The dip and capillary (flow) methods are the most commonly employed⁵.

It is important to employ the minimum of solvent cement and a minimum of softened plastic. The softened plastic must be great enough to provide complete contact and eliminate air bubbles. An excess of solvent reduces the strength of the joint, prolongs setting the bond, and may result in squeezed-out material.

Table 5-3 lists some solvents suitable for bonding glass-reinforced thermoplastics. A dope containing 10-15% dissolved resin is recommended for solvent bonding to compensate for the relatively rough surfaces of GRTP⁹.

TABLE 5-3. SOLVENTS FOR BONDING GRTP's⁹

Base Resin	Suggested Solvents
ABS	^a MEK, MIBK, Methylene Chloride
SAN	MEK, Methylene Chloride
Styrene	Ethylene Ketone, Methylene Chloride
Polyethylene	Solvent bonding not recommended
Polypropylene	Solvent bonding not recommended
Nylon 6	Aqueous Phenol

^aMEK = methylethyl ketone

MIBK = methylisobutyl ketone

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5-4 INDUCTION BONDING

5-4.1 DEFINITION

This bonding method uses induction heating of magnetic materials to develop heat losses in the form of hysteresis and eddy currents when subjected to high frequency alternating current. The magnetic materials consist of fine micron-sized particles or powders (such as magnetic iron oxide) uniformly dispersed in a thermoplastic matrix. Placement of this material at the interface of two glass-reinforced thermoplastic materials will bring the abutting surfaces to their fusion temperature. The fusion temperature is reached from the heat losses generated by the magnetic particles. Thus the magnetic bonding material heats via induction, and the fusion weld of the adjoining material is accomplished by conduction. Uniform contact pressure is essential for the thermal conduction of the two abutting surfaces.

This process requires?

1. A high frequency induction generator designed to supply 2-5 kW output power and 3-30 MHz output frequency
2. A water-cooled copper work coil designed to establish the magnetic field pattern along the bond line
3. A holding fixture—manually or electrically controlled mechanism to locate the workpiece uniformly within the work coil
4. An electromagnetic material supplied as a molded or extruded preform located at the bond interface. Special hot melt or liquid systems can also be employed.

Electromagnetic hot melts are also used. Standard hot melt applicators dispense the hot melt between the two substrates to be bonded with their subsequent reactivation through an RF work coil. This permits maintaining the ultimate hot melt temperatures without heat losses due to open time and heat sink through the substrate.

Some advantages of electromagnetic bonding are:

1. Any thermoplastic material can be bonded to itself plus certain dissimilar plastics. Reinforced plastics with up to 30% filler have been successfully joined.
2. Structural, hermetic, and high pressure seals can be obtained.
3. Rapid, reliable automatic bonding cycles can be obtained in seconds.
4. The physical and chemical properties of the

bond area are similar to the joined materials.

5. No marring of external surfaces occurs.
6. No pretreatment of surfaces is required.
7. The bond area need not be symmetrical, and the size can vary from a small spot to a long continuous length.
8. Storage life of the electromagnetic compound is indefinite.

A major disadvantage is that the materials to be joined are limited to nonmetals.

5-4.2 BONDING TECHNIQUE

The distance between the work coil and the electromagnetic material should be as close as possible, generally, between 1/32 in. to 3/32 in. In many applications, the work coil is set into a nonconductive holding fixture and acts as a pressure medium with direct contact on the surface of the plastic to be bonded.

Most bonding applications are performed between 4-30 MHz with a matching induction generator at a range of 2-5 kW power output.

The electromagnetic material at the bond interface becomes molten when activated and flows. This flow can be directed, if desired, to fuse a greater interfacial bond area than the original contact surface of the electromagnetic layer. However, ideally, the molten flow should be contained and subjected to an internal pressure against the nonconductive thermoplastic bonding surfaces. Thus, a void area should be provided⁶.

The following general expression can be used for a typical tongue and groove joint where maximum physical properties and pressure-type joints are required?

$$A_s = A_m - 0.05 A_v = 0.95 A_v \quad (5-1)$$

where

A_s = cross-sectional area of electromagnetic material

A_v = cross-sectional area of void in the joint.

5-5 ULTRASONIC WELDING

5-5.1 DEFINITION

In ultrasonic welding, high-frequency vibrations in the form of mechanical motion are used to melt the joining surfaces of glass-reinforced parts and fuse them together with a strong molecular bond. Weld strengths are about 70% of the ulti-

mate tensile strength of the glass-reinforced material.

Five components are essential in ultrasonic welding: power supply, converter, horn, fixture, and a stand. The power supply converts a 60 Hz line frequency to 20 kHz. An electrostrictive converter mounted in the stand then converts this electrical energy to 20 kHz mechanical vibratory energy. This is accomplished by the use of a piezoelectric transducer.

The converter is connected to a horn which channels the 20 kHz vibrations to the part being welded. Horns are designed to conform to the part and are constructed of titanium or aluminum.

The stand contains the converter, electronic programmers, pneumatic controls, fixture, pressure device for applying a force by the horn on the part, and sometimes the power supply. The stand also assures proper alignment of the horn and fixture. The fixture supports and aligns the parts to be welded. In all cases the fixture must possess a certain degree of elasticity to guarantee an out-of-phase condition at the joint area. If they vibrate in the same phase, no weld can occur.

5-5.2 WELDING TECHNIQUES

In ultrasonic welding, the vibrating horn contacts one of the mating parts under controlled pressure through a time cycle (usually less than 1 s). Ultrasonic vibrations pass from the horn to the interface or joint resulting in localized heat. The matrix melts, flows, and forms a weld. Both mating halves remain cool except at the joint where the energy quickly is dissipated. After the ultrasonics are turned off, the horn maintains a brief

clamping force until the resin solidifies. The parameters of a 30% glass-reinforced polyester (Valox) are given in Table 5-4 as an example.

Glass-reinforced parts should not be overwelded since this will expose glass fibers at the joint and produce a bond of lower strength.

Besides spot welding, ultrasonics can be used to insert metals into plastic, stake materials to plastics, scan weld flat parts, and degate runner assemblies.

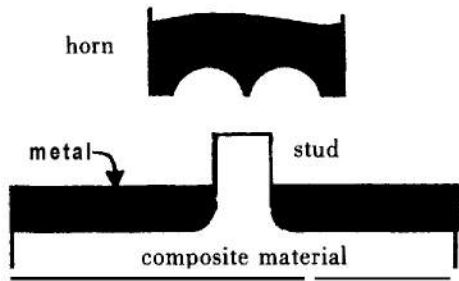
In ultrasonic staking a stud molded onto the plastic part protrudes through a hole in the metal part. The surface of the stud is vibrated with a horn. The vibration causes the stud to melt and reform in the configuration of the horn tip (Fig. 5-11). The advantages of ultrasonic staking are rapid formation of uniform staked heads, tight assemblies due to loss of material memory, nondegradation of the plastic, nonadherence of the plastic to the horn, and the capability of forming more than one stud at a time within the size limitation of the horn³. Tip configuration of the horn will depend upon the application, the grade of resin, and the configuration of the stud.

With the exception of glass-reinforced fluorocarbons, such as polytetrafluoroethylene and fluorinated ethylene-propylene, most all materials can be ultrasonically welded. Table 5-5 compares the welded strength of several glass-reinforced materials. However, horn wear problems can arise from the abrasiveness of the fiberglass. This problem is usually minimal with less than 20% glass. Welds can be made with glass levels between 20 and 35% but some wear will result. Strong welds cannot be assured at levels above 35% due to insufficient fusible resin⁴.

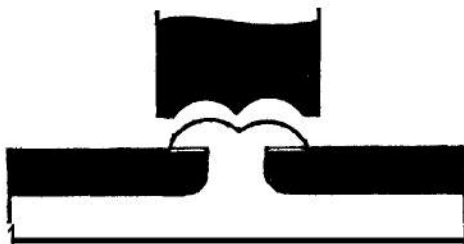
Weldability of any thermoplastic material de-

TABLE 5-4. ULTRASONIC WELDING 30% GLASS-REINFORCED MATERIAL⁸

Weld Time, s	Hold Time, s	Weld Pressure, psi	Horn Amplitude, mil	Scarf Joint, deg	Hermetic Seal?	Burst Pressure, psi
1.0	0.5	60	2.0	45	Yes	1000
0.5	0.5	60	2.0	45	Yes	800
0.5	0.2	60	2.0	45	Yes	800
0.5	0.2	30	2.0	45	Yes	1000
0.5	0.5	60	3.2	45	Yes	1000



(A) Before Staking



(B) After Staking

Figure 5-1. Typical Ultrasonic Staking Operation³

depends on its stiffness or modulus of elasticity ME , density D , coefficient of friction CF , thermal conductivity TC , specific heat SH , and crystalline melting or softening temperature T . A semiempirical "weldability index" has been used for purely qualitative comparisons. It can be calculated for any material using the following equation*:

$$\text{Weldability Index} = \frac{(ME) \times (CF) \times (TC)}{D \times (SH) \times T} \quad (5-2)$$

The higher the index, the greater is the weldability.

In addition, experimental tests are recommended with materials to be welded or staked, etc., to determine the suitability of ultrasonic assembly, especially where dissimilar plastic resin systems are being joined.

Ultrasonic welding can result in joint strength equal to the tensile strength of the unreinforced resin. However, this technique is not recommended for applications requiring a high impact strength in the bonded area.

The following are some recommendations for achieving good welds³:

1. Wall thickness should be at least 0.020 in.

TABLE 5-5. WELDED STRENGTH OF ULTRASONICALLY BONDED GLASS-REINFORCED AND NONREINFORCED THERMOPLASTICS⁹

Base Resin	Glass Content, wt %	Tensile Yield Strength, psi		$\frac{\text{Welded Tensile Strength}}{\text{Ultimate Tensile Strength}} \times 100, \%$
		Ultimate	Welded	
ABS	20	13,500	10,500	79
ABS	0	7,500	6,100	82
SAN	20	15,000	12,500	83
SAN	0	10,000	8,700	83
Styrene	20	12,500	10,500	87
Styrene	30	15,000	12,500	83
Styrene	0	8,000	7,000	89
Polyethylene	20	7,800	5,500	70
Polyethylene	30	10,000	6,600	66
Polyethylene	0	4,200	2,700	64
Polypropylene	20	9,800	6,500	67
Polypropylene	0	5,000	2,900	58
Nylon 6	15	15,800	11,900	75
Nylon 6	0	9,000	6,400	71

2. The size of a single bond is restricted by limitations of available power supplies, but several units can be set up in series to produce continuous bonds on a large part.

3. Parts should be joined immediately after molding. If joined later, predrying may be necessary to provide maximum joint strength. If this is done, parts should be joined as soon as possible after removal from the oven.

4. Provide a small initial contact area such as a "V" bead to concentrate the energy.

5. Design the female part slightly larger.

6. Allow for the flow of molten material.

7. Allow for a slight dimensional change.

8. Locate the joint as close as possible to the point where the ultrasonic tool can be applied.

9. Provide locating pins or tongue-and-grooves for part alignment.

10. Provide proper proportioning of joint elements—avoid tight joints and large mating surfaces.

11. Material must be clean and free of any type of mold spray.

The power ratings of 20-kHz machines have climbed from a few hundred watts to 1600 W. Recently, lower frequency machines of 10-kHz supplying 4000 W are available. With this equipment it is possible to weld 15-in. parts. However, the 10-kHz machines must be housed in an acoustically insulated housing since the frequency is within the audible range.

Miniaturized machines, 40 kHz and 50 kHz, have been developed for light-duty welding. As a result of the high operating frequency, the tooling is reduced significantly.

Portable ultrasonic equipment with power supplies up to several hundred watts is also available¹¹.

5-5.3 ADVANTAGES AND DISADVANTAGES

There are several factors that should be considered in ultrasonic welding. Hygroscopic and high lubricity materials as well as mold release agents, plasticizers, and some colorants can reduce weldability.

Although ultrasonic assembly systems cost more than other systems, they can be completely automated and their cost can be justified in production runs. Fewer clamps, fixtures, drying ovens, and less bonding or curing time usually are involved.

5-6 HOT PLATE WELDING

5-6.1 DEFINITION

Hot plate welding consists of a temperature controlled heating element suitable for simultaneously heating both plastic surfaces to be joined. During heat up of the material on the hot plate, a pressure sufficient to maintain intimate contact between the mating surfaces should be used. As soon as the plastic softens sufficiently, the hot plate is removed and the molten surfaces brought quickly together. The surfaces are held with the minimum possible pressure to remove air bubbles and give intimate contact until the material solidifies. Excessive pressures will result in poor bond strength and heavy flash (Fig. 5-2).

A plate of solid nickel is recommended to resist corrosion from decomposing resins on the plate surface. Tool temperatures run from 150°-480°C (300°-900°F).

5-6.2 WELDING TECHNIQUES

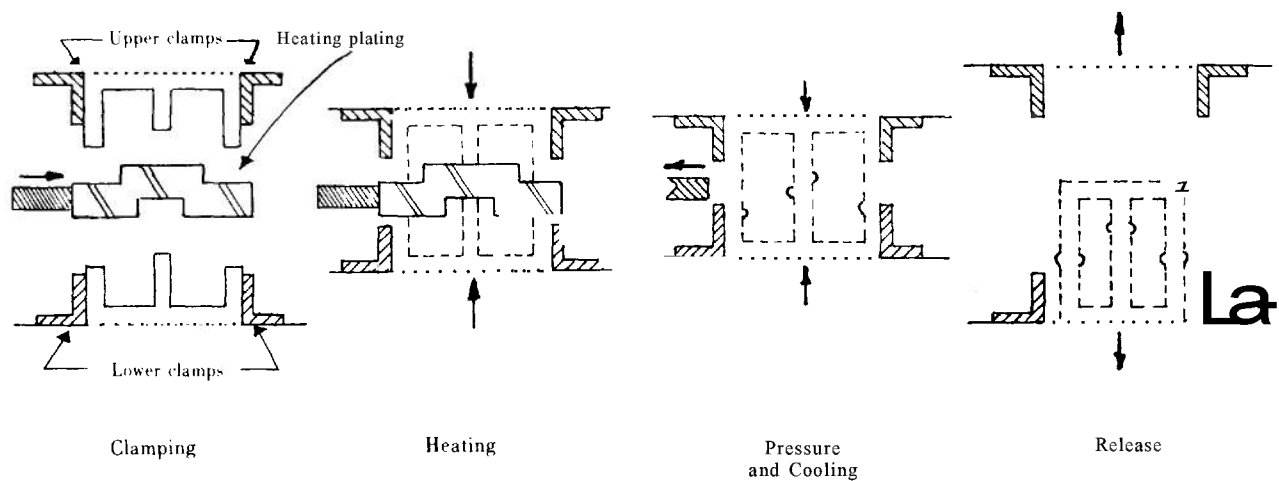
Inasmuch as the melt zone is shallow, the cooling time will be about as short as the heating time. The pressure at the weld surface ranges between 30 and 150 psi.

Semiautomatic and automatic pneumatically or hydraulically operated machines can be used. Pressure controls are required for melt, weld, and clamping pressures. Accurate timers are also required for cycle control. High production runs may use feeding, clamping, and ejection from a conveyor belt where the application permits.

5-7 SPIN WELDING

In spin welding, the surfaces to be joined are pressed together while one part is spun and the other is held fixed. Frictional heat produces a molten zone that becomes a weld when spinning stops. This welding technique is limited to parts with circular joints. It is especially useful for large parts where ultrasonic welding or chemical bonding is impractical.

The edges to be welded should not have deeply grooved sections. A shallow tongue and groove or ledge which facilitates alignment, yet permits contact of all surfaces, is preferred. A completely flat surface is satisfactory, but this requires precise alignment of tools and fixtures. Contact



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Figure 5-2. Sequence of Steps in Contact Heat-Welding Process¹²

time is very short — often a fraction of a second. Pressure should be released and spinning discontinued as soon as the weld is formed. Speeds, pressures, and contact time should be established for each application.

Frictional heat is so intense that it produces almost immediate surface melting without significantly affecting the temperature around the welding area. A dynamic brake is required to stop the tool rapidly to prevent damaging the weld.

5-8 VIBRATION WELDING

Vibration welding is an improved friction welding technique for joining thermoplastic parts. In vibration welding, frictional heat is generated by pressing the surfaces of two plastic parts together and vibrating the parts through a small relative displacement. The displacement can be either linear or angular. The major advantage of this technique lies in its application to non-circular parts, provided that a small relative motion between the parts in the welding plane is possible. Vibration welding also can join circular parts in a specific orientation.

Whatever the configuration, when vibrations cease at the end of the welding cycle, parts are in the exact desired position relative to one another.

After a short cooling time under pressure, the welded parts are released¹³.

Vibration welding machines operate at relatively low frequencies, 90-120 Hz. The amplitude of displacement can be varied in a range of 3-6 mm (0.120-0.240 in.). Joint pressure should be in the range of 1.4-1.7 MPa (200-250 psi). Weld time will generally be between 2 to 3 s plus approximately 1 s hold time. Though slightly longer than typical spin welding and ultrasonic welding cycles, this is much shorter than hot plate welding and solvent cementing cycles¹³.

Very large plastic parts, especially those with complex shapes, have been difficult to weld. With this technique, parts with welding surfaces as long as 50 cm (20 in.) have been successfully joined. The linear method is applicable for all parts, while angular welding is limited to parts with a length to breadth ratio not exceeding 1.5:1. Both methods offer the capability of welding more than one part at a time¹³.

5-9 HOT GAS WELDING

In this joining method a section of extruded rod stock is used as a welding rod and is melted into the joining surfaces with a jet of super-heated air or gas, e.g., nitrogen. Depending upon the equip-

TABLE 5-6. DRIVING AND STRIPPING TORQUES AND PULL-OUT STRENGTHS OF SELF-TAPPING SCREWS IN CELANEX 3300²

Screw Size ^a	Penetration, in.	Pilot Hole Size, in.	Drive Torque, in.·lb	Stripping Torque, in.·lb	Strip/Drive Ratio	Strip/Drive Differential, in.·lb	Pull Out Strength, lb
Plastite							
2-28	3/16	0.073	1	5	5:1	4	—
	1/4	.073	2	7	3.5:1	5	—
4-20	3/16	.098	2	10	5:1	8	—
	1/4	.098	3	13	4.2:1	10	—
6-19	1/4	.116	4	22	5.5:1	18	350
	7/16	.116	7	48	7:1	41	850
8-16	5/16	.149	9	40	4.14:1	31	650
	1/2	.149	12	75	6.2:1	63	1300
10-14	5/16	.173	11	55	5:1	44	750
	1/2	.173	17	100	6:1	83	1450
Hi-Lo, Shank-Slotted							
8-18	5/16	0.130	4	20	5:1	16	340
	1/2	.130	6	36	6:1	30	—
9/32-16	5/16	.230	11	54	5:1	43	700
	1/2	.230	15	105	7:1	90	1250
Hi-Lo, Blunt Point							
8-18	5/16	0.130	7	28	4:1	21	430
	1/2	.130	10	45	4.5:1	35	—
	5/16	.230	25	80	3:1	55	930
9/32-16	1/2	.230	30	132	4.4:1	102	1700
Type BF							
4-24	5/16	0.093	4	11	3:1	7	430
	1/2	.093	4	15	4:1	11	510
6-20	3/8	.120	4	16	4:1	12	530
	1/2	.120	4	28	7:1	24	630
8-18	3/8	.144	5	26	5:1	21	670
	1/2	.144	6	35	6:1	29	840
10-16	3/8	.169	6	30	5:1	24	800
	1/2	.169	9	43	5:1	35	1000
Swageform B							
4-24	5/16	0.093	2.5	9	3.5:1	6	350
	1/2	.093	2.5	16	6:1	13	390
6-20	3/8	.120	3	18	6:1	15	590
	1/2	.120	4	24	6:1	20	600
8-18	3/8	.144	5	22	4.5:1	17	770
	1/2	.144	8	28	3.5:1	20	790
10-16	3/8	.169	6	23	4:1	17	780
	1/2	.169	9.5	30	3:1	20	950
Swageform							
10-32	3/8	0.166	9	25	3:1	16	760
	1/2	.166	12	30	2.5:1	18	950
1/4-20	3/8	.221	9	63	7:1	54	730
	1/2	.221	11	70	6:1	59	1200

^aSwageform B' thread-forming screws, Type 'BF' thread-cutting screws (Parker-Kalon Division, USM Corporation, Clifton, NJ); Plastite' thread-forming screws (Midland Screw Corporation, Chicago, IL); and 'Hi-Lo' thread-forming (blunt point) and thread-cutting (shank-slotted) screws (National Lock Fasteners, Rockford, IL).

ment being used, gas temperatures of 315° - 650° C (600° - 1200° F) can be achieved. The weld bead can then be finished flush with the part surface.

During welding, care must be taken to preclude excessive application of heat since, at the gas temperature used, degradation of the resin could occur. Bond tensile strengths usually are about 70% that of the parent unreinforced resin. For best results, parts should have beveled edges at the plane of juncture which are then butted together to form a V-shaped slot. The materials also must be clean and dry.

5-10 MECHANICAL FASTENING

GRTP can be joined by many mechanical means. Some of the popular methods are discussed in the paragraphs that follow.

5-10.1 SELF-TAPPING SCREWS

Mechanical joining can be done conveniently with self-tapping screws. This method requires drilling or molding a pilot hole into the part. It is important that a close tolerance (± 0.001 in.) to the supplier's recommended pilot hole size be maintained for optimum properties.

Table 5-6 presents the optimum pilot hole diameter, and driving and stripping torques of self-tapping screws for 30% glass-reinforced polyester. Both thread forming screws and thread cutting screws can be used.

Driving torque values indicate the torque necessary to drive the screws into the pilot holes. Stripping torque values indicate the tightening torques which will strip the threads formed by the self-tapping screws. In many applications, a low driving torque with a substantial drive/strip ratio is of primary importance.

The higher the torque used to tighten self-tapping screws (seating torque), the greater the clamping force which will be exerted between the components assembled. Screw manufacturers generally recommend a seating torque $1/2$ to $3/4$ of the stripping torque value².

In some applications, the holding strength is the primary consideration. The driving and stripping torques may be of minor importance, although the drive torque must not be excessive and the drive/strip ratio must be reasonable (about 1:3). The holding strength is measured by pull-out force (the force necessary to pull out, without turning, the self-tapping screws). In still

other applications, loosening due to vibration is important².

In general, screw holes in studs or bosses for GRTP should be designed with less interference because of the greater hardness of these materials. It is recommended that the original design be made with 0.007-in. interference as opposed to 0.030 in. for unreinforced material. Then build up the interference in 0.004-0.005-in. increments until the correct interference is reached¹⁴. Holes should be designed with a chamfer at the opening, to lead the screw in, and a radius at the bottom of the core. Wall thickness around the hole should be 75-100% of the diameter of the screw. Useable depth of the core is about 1.5 times the diameter of the screw¹⁴.

Repeated assembly operations are not recommended. Also, a minimum torque should be used to keep the screw assembly stress within the design limit of the material. The amount of torque which can be placed on the screw depends on the cross-sectional area of the boss and/or the total number of threads. Since sufficient threads can generally be provided to take resultant loads, applied torque becomes dependent on the boss cross section³.

If self-tapping screws are used in an assembly designed to operate in a chemical environment, the assembly should be evaluated in actual operating conditions prior to acceptance for production.

Boss caps are designed to reinforce the boss against the expansion force exerted by tapping screws. It is a cup-shaped metal ring which is pressed onto the boss by hand, with an air cylinder, or with a light-duty press (see Fig. 5-3).

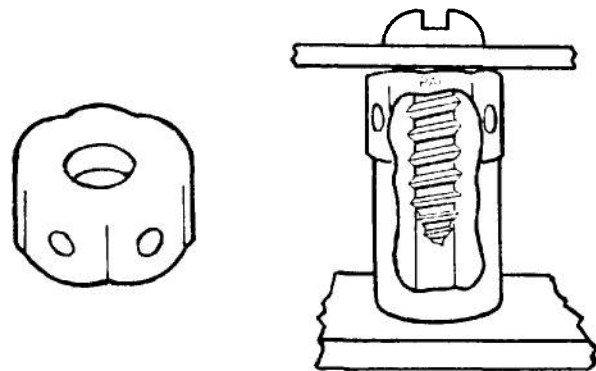
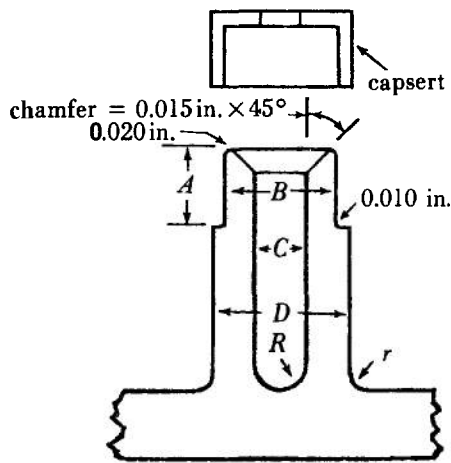


Figure 5-3. Boss Cap³

Although a boss cap does not increase the load bearing capacity of the boss, it does promote positive alignment of the screw and increases the initial driving torque required to insert the screw. This reduces the possibility of stripping boss threads during insertion.

A self-tapping screw with boss cap can be torqued 40-100% higher than pressed-in or molded-in inserts. It will also limit thermal expansion of the boss.

Fig. 5-4 illustrates recommended boss cap design. The boss cap should fit snugly on the boss. To prevent torquing stresses from concentrating in the boss threads, thread length should be 1.25-1.75 times the thread diameter³. If there is no gap between the joined parts, the clamping load will be distributed evenly over the face of the boss permitting the use of 25-40% higher initial torques³.



Type 23 Screw Thread Size	Polycarbonate (Lexan) Boss Dimensions, in.					
	A	B	C	D	R	r
# 6-32	0.135	0.208	0.116	0.276	0.058	0.015
#8-32	0.151	0.248	0.1405	0.328	0.070	0.015
# 10-24	0.182	0.287	0.159	0.380	0.079	0.020

Figure 5-4. Recommended Boss-Cap Design for Glass-Reinforced Polycarbonate³

TABLE 5-7. RECOMMENDED CLEARANCE FOR MACHINE SCREWS³

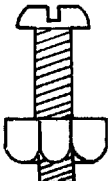
	Screw Size	Hole Diameter, in.
	#2	0.696
#4	0.122	
#6	0.148	
#8	0.174	
# 10	0.200	
#12	0.226	
1/4	0.260	
5/16	0.323	
3/8	0.385	

TABLE 5-8. RECOMMENDED TORQUE FOR FILLISTER HEAD SCREWS, in. • lb (Ref. 3)

Screw Size	Unreinforced Lexan	10% GR Lexan 500	20% GR Lexan 3412	40% GR Lexan 3414
#2	0.2	0.3	0.4	0.5
#4	0.5	0.7	0.9	1.3
#6	1.1	1.4	1.8	2.6
#8	1.8	2.5	3.2	4.6
#10	2.9	4.0	5.1	7.3
#12	4.4	5.9	7.7	11.0
1/4	7.0	9.4	12.2	17.4
5/16	14.0	18.9	24.5	35.0
3/8	24.4	33.0	42.8	61.1

TABLE 5-9. RECOMMENDED TORQUE FOR PAN HEAD SCREWS, in. • lb. (Ref. 3)

Screw Size	Unreinforced Lexan	10% GR Lexan 500	20% GR Lexan 3412	40% GR Lexan 3414
#2	0.4	0.6	0.8	1.1
#4	1.0	1.4	1.8	2.6
#6	2.0	2.7	3.5	5.0
#8	3.4	4.6	6.0	8.6
# 10	5.5	7.4	9.5	13.6
# 12	8.1	10.9	14.1	20.2
1/4	12.7	17.1	22.2	31.1
5/16	25.1	33.8	43.8	62.6
3/8	43.8	59.2	76.7	109.6

TABLE 5-10. RECOMMENDED TORQUE FOR PAN, FILLISTER HEAD SCREWS WITH WASHERS, in. • lb. (Ref. 3)

Screw Size	Washer Size (OD – ID), in.	Unreinforced Lexan	10% GR Lexan 500	20% GR Lexan 3412	40% GR Lexan 3414
# 2	OD – 0.187 ID – 0.094	0.7	1.0	1.2	1.8
	OD – 0.343 ID – 0.094	3.0	4.0	5.2	7.4
# 4	OD – 0.25 ID – 0.125	1.6	2.2	2.9	4.1
	OD – 0.437 ID – 0.125	6.2	8.3	10.8	15.5
# 6	OD – 0.281 ID – 0.156	2.4	3.2	4.2	5.9
	OD – 0.562 ID – 0.156	12.7	17.1	22.2	31.7
# 8	OD – 0.375 ID – 0.188	5.4	7.3	9.5	13.6
	OD – 0.625 ID – 0.188	18.3	24.7	32.0	45.8
# 10	OD – 0.406 ID – 0.208	7.3	9.8	12.7	18.2
	OD – 0.734 ID – 0.208	29.6	40.0	51.8	74.0
# 12	OD – 0.437 ID – 0.240	9.1	12.3	15.9	22.7
	OD – 0.875 ID – 0.240	48.0	64.9	84.1	120.1
114	OD – 0.500 ID – 0.281	13.4	18.1	23.5	33.6
	OD – 1.000 ID – 0.281	72.3	97.7	126.6	180.8
5/16	OD – 0.625 ID – 0.344	26.7	36.1	46.8	66.8
	OD – 1.125 ID – 0.344	112.6	152.1	197.1	281.6
3/8	OD – 0.734 ID – 0.406	44.1	59.6	77.2	110.3
	OD – 1.250 ID – 0.406	164.7	222.3	288.2	411.6

5-10.2 MACHINE SCREWS

Machine screws commonly are used to assemble components made of GRTP. Recommended clearance hole diameters are provided by material suppliers. Those for polycarbonate (Lexan) are given in Table 5-7. To insure optimum component reliability, screw torque must be specified after careful consideration of the following:

1. Bearing force of the screw head or washer
2. Thread shear stress
3. Boss tensile stress.

All of these variables are interrelated, which requires each parameter to be matched with the corresponding screw configuration, screw size, and particular grade of material. Those for polycarbonate (Lexan) are given in Tables 5-8 through 5-12.

TABLE 5-11. TORQUE FOR MAXIMUM ALLOWABLE STRESS IN BOSS, in. •lb (Ref. 3)

Screw Size	Unreinforced Lexan	10% GR Lexan 500	20% GR Lexan 3412	40% GR Lexan 3414
#2	0.6	0.8	1.1	1.5
#4	1.3	1.8	2.3	3.3
#6	2.5	3.4	4.3	6.2
#8	4.2	5.6	7.3	10.4
#10	6.5	8.7	11.3	16.2
#12	9.5	12.8	16.6	23.7
1/4	14.7	19.9	25.8	36.8
5/16	28.8	38.8	50.3	71.9
3/8	49.7	67.1	86.9	124.2

TABLE 5-12. THREAD SHEAR STRESS TORQUE PER ENGAGED LEXAN THREAD (MALE OR FEMALE), in. •lb (Ref. 3)

Screw Size	Unreinforced Lexan	10% GR Lexan 500	20% GR Lexan 3412	40% GR Lexan 3414
#2	0.09	0.12	0.16	0.23
#4	0.21	0.28	0.37	0.53
#6	0.4	0.54	0.69	1.0
#8	0.6	0.81	1.0	1.5
#10	1.0	1.4	1.8	2.5
#12	1.4	1.9	2.4	3.4
1/4	2.2	2.9	3.8	5.5
5/16	3.9	5.3	6.9	9.8
3/8	6.5	8.8	11.4	16.2

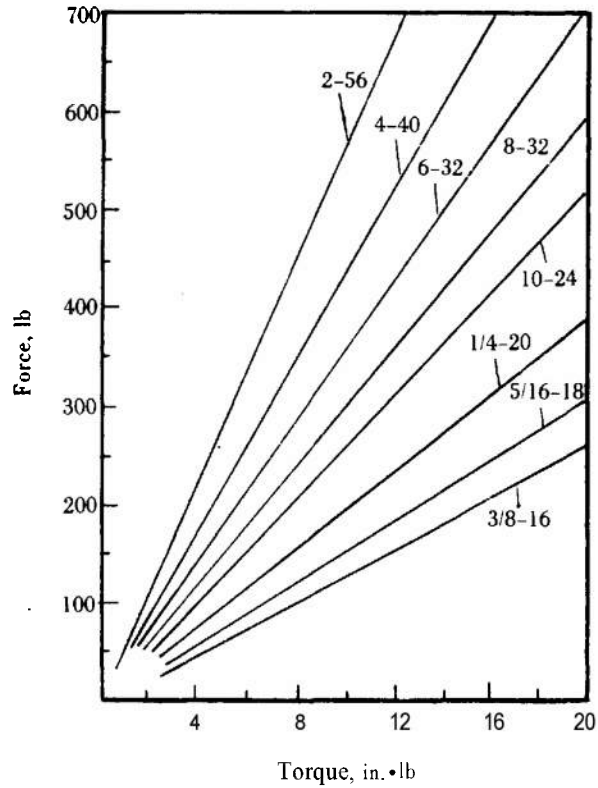


Figure 5-5. Screw Torque vs Force for Glass-Reinforced Polycarbonate (Lexan)³

The curves shown in Fig. 5-5 were developed for glass-reinforced polycarbonate, using the power screw equation which relates applied torque to the resulting force created by the screw. This information is useful when calculating stresses induced by threaded fasteners with nonstandard head sizes.

In applications requiring the use of a metal screw and a threaded boss, the boss diameter must be equal to twice the thread diameter (Fig. 5-6). This recommendation should generally be followed for screws up to 3/8 in. in diameter³.

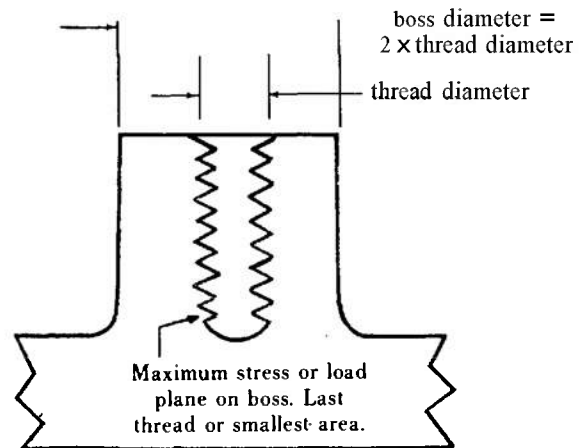


Figure 5-6. Recommended Thread and Boss Structure³

5-10.3 MOLDED-IN INSERTS

Metal inserts may be molded into GRTP with satisfactory results. This is due to the superior coefficient of expansion and higher design stress limits of composite materials. Inserts of steel, brass, and aluminum were found to be acceptable when the following precautions were followed²:

1. Use an insert with a coarse knurl for maximum holding power. The knurl should end below the surface of the plastic.

2. Radius all sharp corners on the insert. Sharp corners on the knurl should be broken by tumbling or grit blasting.

3. Inserts should have blind internal holes as opposed to through holes and have a generous radius or spherical shape at the closed end.

4. The open end of the insert should project above the surface of the molding.

5. Inserts should be at the temperature recommended by the material supplier when molding to reduce thermal stresses.

6. Wall thickness of the material around the insert should be no less than half the insert OD.

7. All incompatible chemicals, such as oil, should be removed from the insert.

A simple pull-out or torque retention groove may prove to be sufficient for some applications. A flat surface on one or two sides of the insert may also provide sufficient torque strength.

Sharply knurled inserts should be avoided when possible because they produce a notch effect in the material.

Generally, a part containing molded-in inserts will function properly at normal room conditions. Pretesting parts under anticipated service conditions is recommended to determine their suitability for chemical, high temperature, and thermal cycling environments.

5-10.4 PRESS FIT INSERTS

Combinations of plastic and/or metal can be satisfactorily assembled using the press fit technique, provided correct diametral interferences are determined during design.

Holding strength over an extended period of time is of prime importance and is governed by the creep characteristics of the material. Creep reduces effective diametral interference. Thus the effective pressure is reduced, resulting in a loss of holding power. Since this is a known phenomenon for most materials, it is impractical to

design for an interference which would induce a stress above the creep limit of the material.

The relationship of maximum stress, caused by press fitting a shaft or insert in a plastic hub, to diametral interference (ΔD) is expressed as³:

$$\Delta D = \frac{S_d D_s}{L} \left(\frac{L + \mu_h}{E_h} + \frac{L - \mu_s}{E_s} \right), \text{ in.} \quad (5-3)$$

and

$$L = \frac{1 + \left(\frac{D_s}{D_h} \right)^2}{1 - \left(\frac{D_s}{D_h} \right)^2}, \text{ dimensionless}$$

where

S_d = design stress, psi

D_h = outside diameter of hub, in.

D_s = diameter of shaft, in.

E_h = tensile modulus of elasticity of hub, psi

E_s = modulus of elasticity of shaft, psi

μ_h = Poisson's ratio of hub material, dimensionless

μ_s = Poisson's ratio of shaft material, dimensionless

L = geometry factor, dimensionless.

The force required to press fit two parts may be approximated by use of the following equation³:

$$F = \pi f P D_s T, \text{ lb} \quad (5-4)$$

and

$$p = \frac{S_d}{L}, \text{ psi}$$

where

F = assembly force, lb

f = coefficient of friction, dimensionless

P = joint pressure, psi

D_s = diameter of shaft, in.

T = length of press fit surfaces, in.

S_d = design stress, psi

L = geometry factor, dimensionless.

The coefficient of friction f is dependent upon many factors and varies among applications. The coefficients listed in Chapter 3 may be used as approximations for rough strength calculations. For greater accuracy, tests on prototype parts are recommended.

A change in operating temperature and dissimilar coefficients of thermal expansion can affect the amount of stress around the shaft. Press-fits should be designed for anticipated operating conditions, while keeping in mind other potential conditions to which the part may be exposed.

5-10.5 ULTRASONIC INSERTS

Ultrasonic insertion is a fast and economical method of installing metal inserts into parts. This technique offers a high degree of mechanical reliability with excellent pull-out and torque retention combined with savings resulting from rapid production cycles. If the assembly is properly designed, ultrasonic insertion results in lower residual stress compared to molded-in or pressed-in techniques since a uniform melt occurs and a minimum amount of thermal shrinkage is involved.

Friction, caused by ultrasonic vibrations, melts a thin film of resin at the metal-plastic interface. Pressure from the ultrasonic tool directs the insert into the cored or machined hole. When the energy source is removed, the molten area surrounding the flutes rapidly freezes securing the

insert. Residual stresses in the boss are minimized because only a very thin film of the resin is melted. Because friction energy is concentrated at a point, melting is rapid and insertion time is relatively fast.

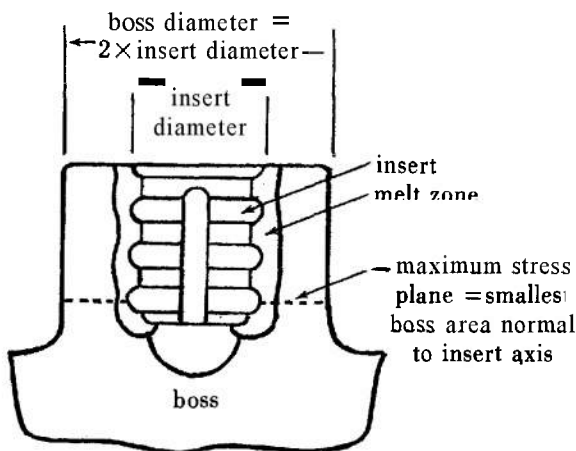
In some cases, ultrasonic energy can be directed from the vibrator through the thermoplastic material to the interface. For most applications, energy should be transferred through the metal insert. Experimentation will quickly reveal the preferred medium for energy transfer in a specific application.

There are two basic insert designs, straight and tapered, as shown in Fig. 5-7.

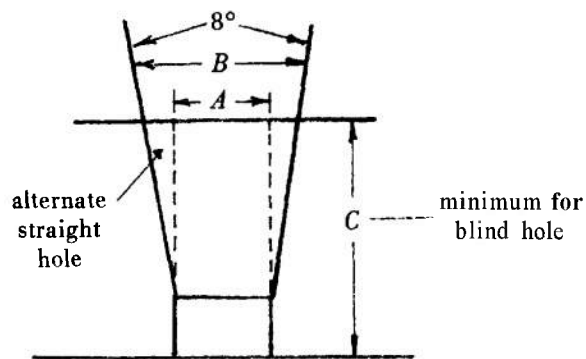
Table 5-13 illustrates the parameters of ultrasonic insertion of various screws in a 30%-glass-reinforced polyester (VALOX).

5-10.6 RIVETS

Conventional riveting equipment and procedures can be used with GRTP. Care must be exercised to minimize stresses induced during the fastening operation. To do this, the rivet head should be 2.5-3 times the shank diameter. Also, rivets should be backed with either plates or washers to



(A) Straight Insert



(B) Tapered Insert

Figure 5-7. Ultrasonic Insert Design³

TABLE 5-13. ULTRASONIC INSERTION OF 30% GLASS-REINFORCED POLYESTER (VALOX)⁷

Insert Thread Size	Hole Diameter, in.	Air Pressure, psi	Insert Time, s	Pullout Strength, lb
4-40	0.150	50	1.0	240
6-32	0.180	50	1.0	340
8-32	0.201	50	1.0	770
10-32	0.234	50	1.0	880
¼-20	0.323	60	2.0	1450

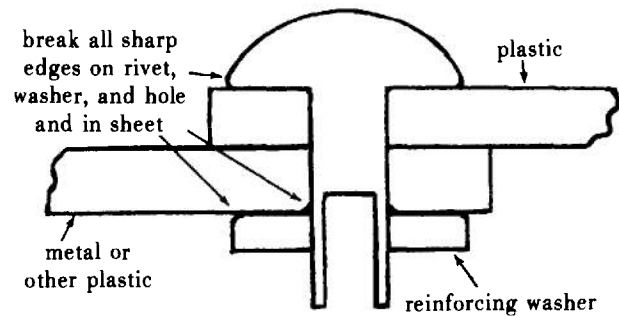


Figure 5-8. Recommended Riveting Procedure for Polycarbonate (Lexan)³

avoid high localized stresses (Fig. 5-8). Fastening procedures should be established to control compressive stress under the fastener head.

Drilled holes rather than punched holes are preferred for fasteners. If possible, fastener clearance in the hole should be at least 0.010 in. to maintain a plane stress condition at the fastener³.

5-10.7 EXPANSION INSERTS

Expansion inserts are placed in predrilled or premolded holes and expanded against the walls by insertion of a screw. Torsional resistance and pull-out retention are obtained by embedding the knurls into the material. The inserts can be obtained with or without heads, depending on design requirements.

A line-to-line condition should be maintained prior to expanding the insert. The total diametral expansion of the insert into the material should not exceed the recommended diametral interference for press-fits. A complete analysis of the insert should be made to determine its total expansion prior to selecting the proper hole size. Material thickness around the insert should not be less than 0.9 times the final outer radius of the insert³.

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CHAPTER 6

PART DESIGN TECHNIQUES

Factors—part shrinkage, dimensional tolerances, warpage, drafts and undercuts, location of holes, fillets and radii to promote resin flow and reduce stress concentration, wall thickness, weld and parting lines to improve appearance and avoid areas of high stress concentration, and the introduction of ribs, bosses and studs, and metal inserts to improve strength—are treated. Recommended safety factors as a function of load are given.

6-1 INTRODUCTION

It is difficult to generalize about part design because of the broad spectrum of properties and various processing methods involved in glass-reinforced thermoplastics (GRTP). As a rule, part design of GRTP starts with the appropriate design for the unreinforced counterpart material.

The graphs and tables of Chapter 3 illustrate the result of glass reinforcement. For example, tensile strength is improved, elongation decreases, and rigidity increases as does deflection temperature. Therefore, GRTP items can be designed with less material than their unreinforced counterparts. Ribs, flanges, or strengthening beads can be smaller or in some instances eliminated.

Some of the specific changes in part design that should be considered when using GRTP are discussed. However, a good practice when designing a part is to consult a mold designer experienced with GRTP and the material supplier for helpful suggestions.

6-2 PART SHRINKAGE, DIMENSIONAL TOLERANCES, AND WARPAGE

The shrinkage of GRTP is inversely proportional to the glass content. Typical shrinkage of GRTP is 1/3 to 1/2 that of the unreinforced resin. To aid the designer, typical mold shrinkage for GRTP is presented in Chapter 3 under the specific resin system.

Part shrinkage is dependent upon many factors such as: material anisotropy, part thickness, mold design (gate size and location), mold temperature, melt temperature, and processing variables (i.e., injection pressure and speed). It is necessary to start with a prototype tool to determine exact shrinkage of complex parts, parts with varying wall thicknesses, or those with large anisotropic shrinkages.

All glass-reinforced materials exhibit anisotropic mold shrinkage. Shrinkage in the flow direction is less than the transverse shrinkage because of the orientation of the fibers in the flow direction. The difference will vary with fiber length, percentage of glass fibers, and resin system. An average difference is approximately 50%, with the shrinkage in the flow direction being the lesser.

Another factor in shrinkage is wall thickness. Thicker wall sections will shrink more than thin ones. Also high molding pressure areas will shrink less than low pressure areas. Shrinkage will also increase as mold temperature increases.

Edge turning (Fig. 6-1) is preferable to edge thickening as a means of providing edge rigidity and eliminating warpage when minimum thickness is used.

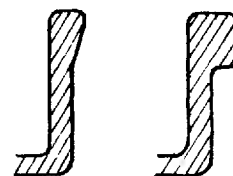
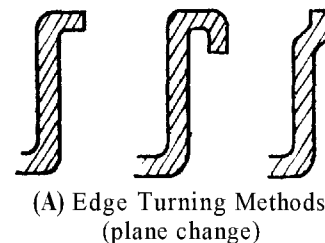


Figure 6-1. Edge Stiffening'

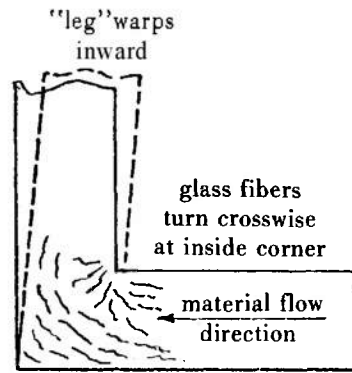
One particular warpage problem is encountered frequently when glass fiber reinforced resin flows around a corner in an L-shaped or U-shaped cross section. There is a tendency for the "L" or "U" to close inward. This is caused by the orientation of the glass fibers at the inner and outer areas of the bend. As the material flows around the bend, glass fibers in the melt stream can maintain their alignment in the flow direction at the outer corner of the bend better than at the inner corner. At the inner corner, the fibers bunch up and are turned crosswise or in random directions. Since glass fiber reinforced materials shrink more in the transverse direction than in the direction of material flow, the molding shrinks slightly more at the inside corner of the bend than at the outer corner, and the upper leg of the "L" moves inward, as shown by the dotted lines in Fig. 6-2 (A). Remedies which have been successfully used to overcome this type of warpage problem are shown in Fig. 6-2 (B).

Various parts have been designed to close tolerances with GRTP. For example, small threads and gears have been designed and molded to tolerances from 0.00025-0.0005 in.

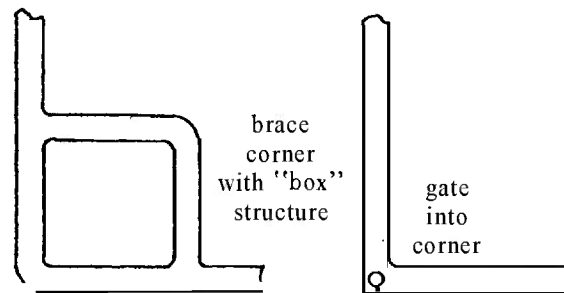
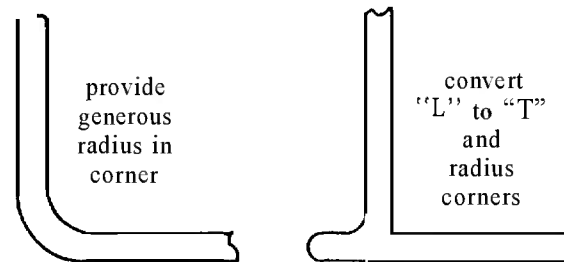
6-3 DRAFT AND UNDERCUTS

Because of the lower shrinkage of GRTP and their higher stiffness compared to unreinforced materials, more draft should be designed into the part to facilitate ejection from the mold. Generally 0.5-3 deg is recommended for injection molding for core pins and cavity walls. However, a minimum of 1 deg is recommended on surfaces parallel to mold movement. This should not be considered a hard and fast rule. Where mandatory, glass and other GRTP parts have been designed and molded with little or no draft. Achieving the no-draft condition requires that a sufficient number of positive knockout pins be strategically placed. If possible, sleeve knockouts should be used on long core pins, and blade knockouts should be used for long, deep walls or ribs. These knockout facilities also permit venting of trapped air and gases³.

Zero draft can be achieved in some areas by use of slides in the mold. Also, zero draft right angles or acute angles can be obtained by assuring that the draft-free surface lies at an angle to the direction of mold movement. This will influence the placement of ribs, bosses, etc., throughout the part.



(A) Warpage



Submarine gate

(B) Remedies

Figure 6-2. Warpage Due to Flow Around Corners²

In hot-flow stamping (compression molding), a draft of 1-3 deg is recommended for depths of 0.25-6 in.; over 6 in. a draft of 3 deg plus is suggested. Draft is required on all surfaces perpendicular to the parting line.

Deep undercuts should be avoided in injection molding since the stiffness of GRTP makes ejection

tion unfeasible. External undercuts can be produced by use of slides or split molds. If less than 1/16 in. deep and well rounded, external undercuts may be molded without slides or split molds.

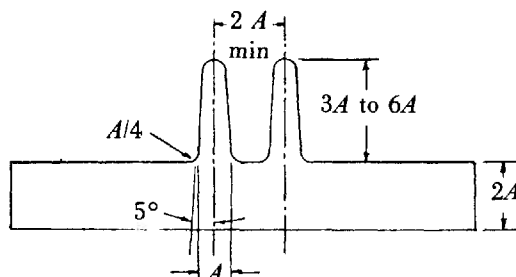
The greater the amount of texture or grain designed into the part, the larger amount of draft should be provided for ejection. A reliable factor for injection molding is to allow 1 deg of draft/inch for each 0.001 in. of texture depth.

6-4 RIBS

Ribs, flanges, and beads are used to increase strength and rigidity without thickness. They improve material flow and control warpage. Normally, they are located at the juncture of two walls, perpendicular to the parting line. Decorative beads or surface effects are often added opposite a rib to hide the effects of shrinkage.

It is recommended, however, that a GRTP part be designed with a provision for ribs but without ribs at the start because its greater strength and reduced shrinkage should make ribs unnecessary³. Ribs can then be added later should they be found necessary. With glass-reinforced materials, the rib design should be originated with a height only 1-1.5 times the wall thickness and less than 0.5 the thickness of the adjacent wall. A fillet should be added at the point at which the rib joins the wall, and the rib should have a 1 deg minimum draft on each side for easy ejection from the mold. Proper proportions for a 30% glass-reinforced polyester are shown in Fig. 6-3.

Where sink is of no concern, ribs can be located wherever strength is needed, and they may be as thick as 70-90% of the adjacent wall thickness.



These proportions for reinforcing ribs will minimize shrinkage and sink marks.

Figure 6-3. Proper Rib Proportions²

However, thick ribs can change dimensions due to shrinkage in the ribs and must be considered in the design.

If ribbing is used in domed or contoured parts, it should conform to the exterior surface contour of the part and the height should generally be no greater than 0.75 in. Fig. 6-4 shows poor and good contoured rib design².

6-5 BOSSES AND STUDS

Bosses are used to reinforce holes in the part and to provide mounting locations. Solid bosses are called studs. Bosses must be molded with rounded corners and adequate fillet radii. They usually are located in a corner or juncture of two or more surfaces to minimize the effects of sinking. The problem of shrink marks is lessened with GRTP because of their reduced shrinkage. It is generally recommended that the height of the boss be limited to twice its diameter. Vertical surfaces should have at least a 1 deg draft per side. Recommended designs are shown in Fig. 6-5.

Shallow bosses are possible provided generous radii and fillets are incorporated to prevent bridging. Bosses deeper than 3 times wall thickness have a tendency to be resin rich at the extreme material flow. Long bosses should also be designed with adequate taper in order to facilitate removal from the mold. Deep holes and core pins should be polished to remove all undercuts caused by lathe turning especially since GRTP materials possess greater rigidity and do not respond with the resiliency of their unreinforced counterparts³.

When using solid bosses (studs), the base diam-

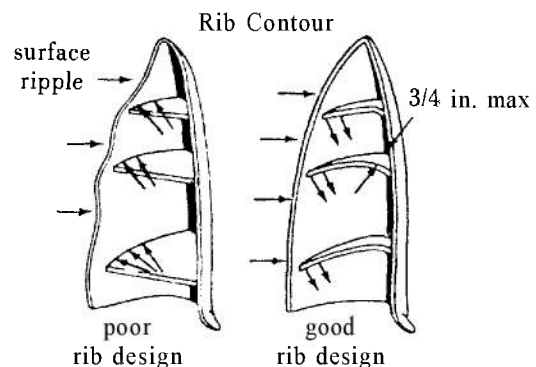


Figure 6-4. Poor and Good Rib Usage²

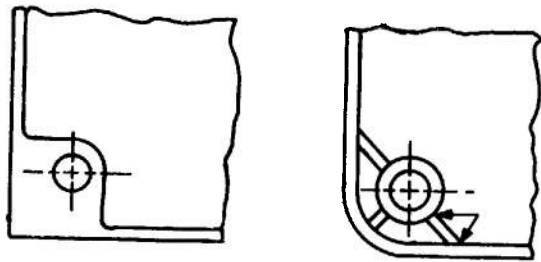
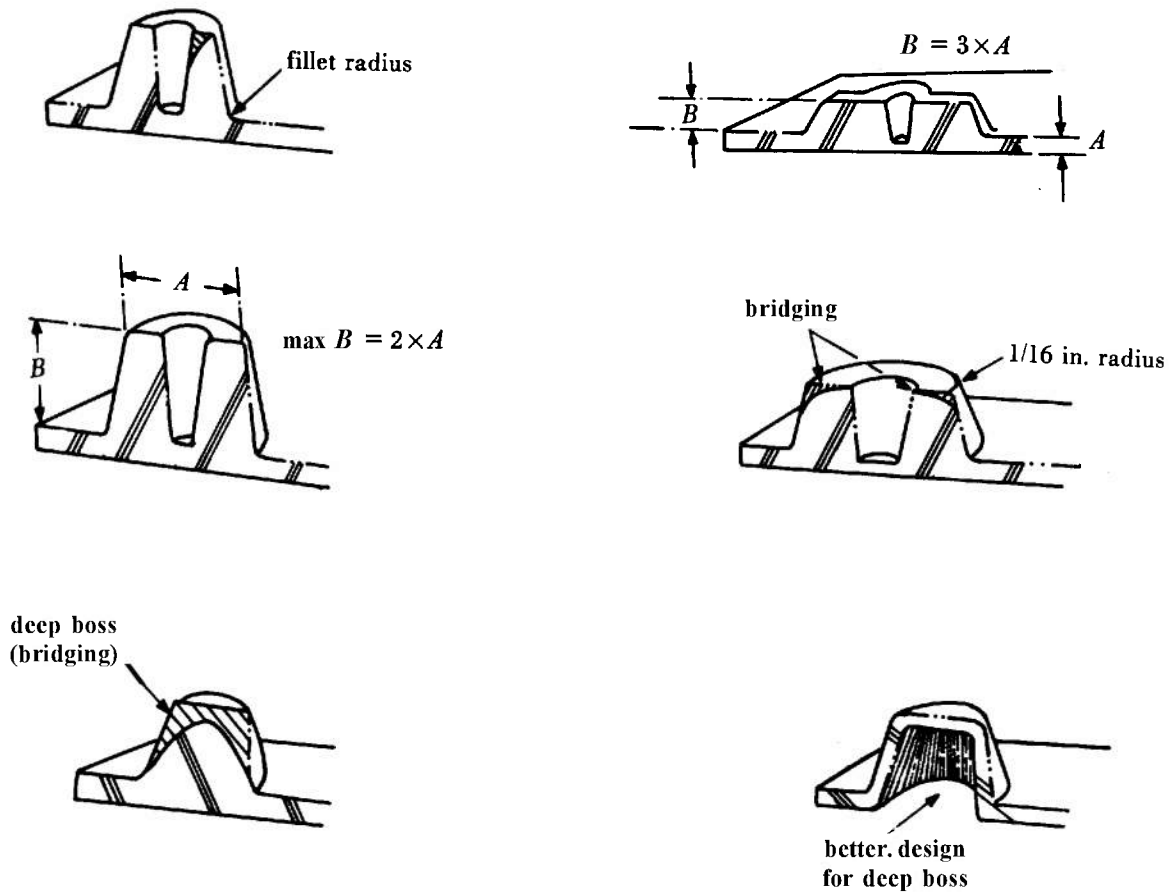


Figure 6-5. Design of Bosses^{2,4}

eter should be smaller in dimension than the thickness of the wall from which it protrudes. Therefore it is preferable to core out the center of bosses so that the side wall thickness is less than the main wall thickness.

In a contoured part, the boss should, where possible, be located at the apex of angles where the surface contour changes abruptly. This is shown in Fig. 6-6. A bubbler used on the cavity side of the mold opposite the boss often will eliminate or minimize sink on the outside wall².

Lastly, adequate venting of injection molds on studs, bosses, or any extended section is required to prevent the entrapment of hot gases in the mold.

6-6 HOLES

Screw holes in studs or bosses can be designed with less interference because of the greater hardness of GRTP. It is recommended that the original part design be made with 0.007-in. interference. The interference should be built up in increments of 0.004 or 0.005 in. at a time until the correct interference is achieved.

Holes should be designed with a chamfer at the opening, to lead the screw in, and with a radius at the bottom of the core. The wall thickness around the hole should be 75-100% of the diameter of the screw. The useable depth of the core is 1-1.5 times the diameter of the screw.

Hole-to-hole distance and distance of hole from

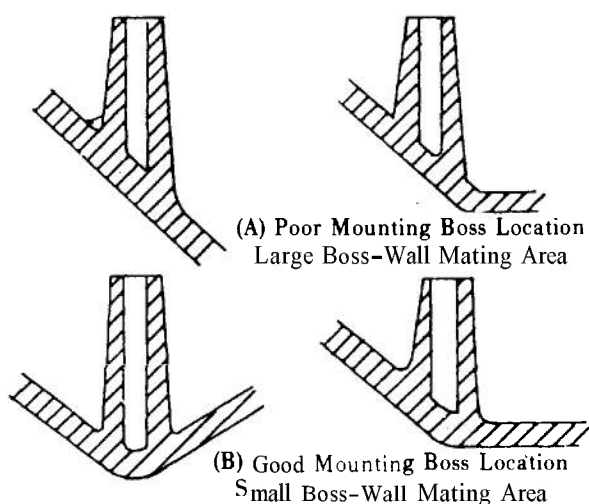


Figure 6-6. Poor and Good Boss Location²

edge of part should be at least one diameter of the hole. If the hole is threaded, the distance should be increased to three times the diameter because of stress concentration.

In hot-flow stamping, through holes are easier to mold and give support to core pins. Blind holes should be limited in depth to two times the diameter of the hole. Also, a stepped design in blind holes permits more depth for hole diameter. In addition, this also reduces wall thickness and die costs.

Holes parallel to parting lines require core pulls and a 1/64-in. vertical step (minimum) should be provided at the open end of the hole⁴. Fig. 6-7 illustrates recommended hole design.

6-7 FILLETS AND RADII

GRTP are characterized by greater rigidity and are more susceptible to notch-type impact of failure than nonreinforced materials. Therefore all sharp radii must be eliminated to promote resin flow to reduce stress concentrations and notch-sensitive failure of the part.

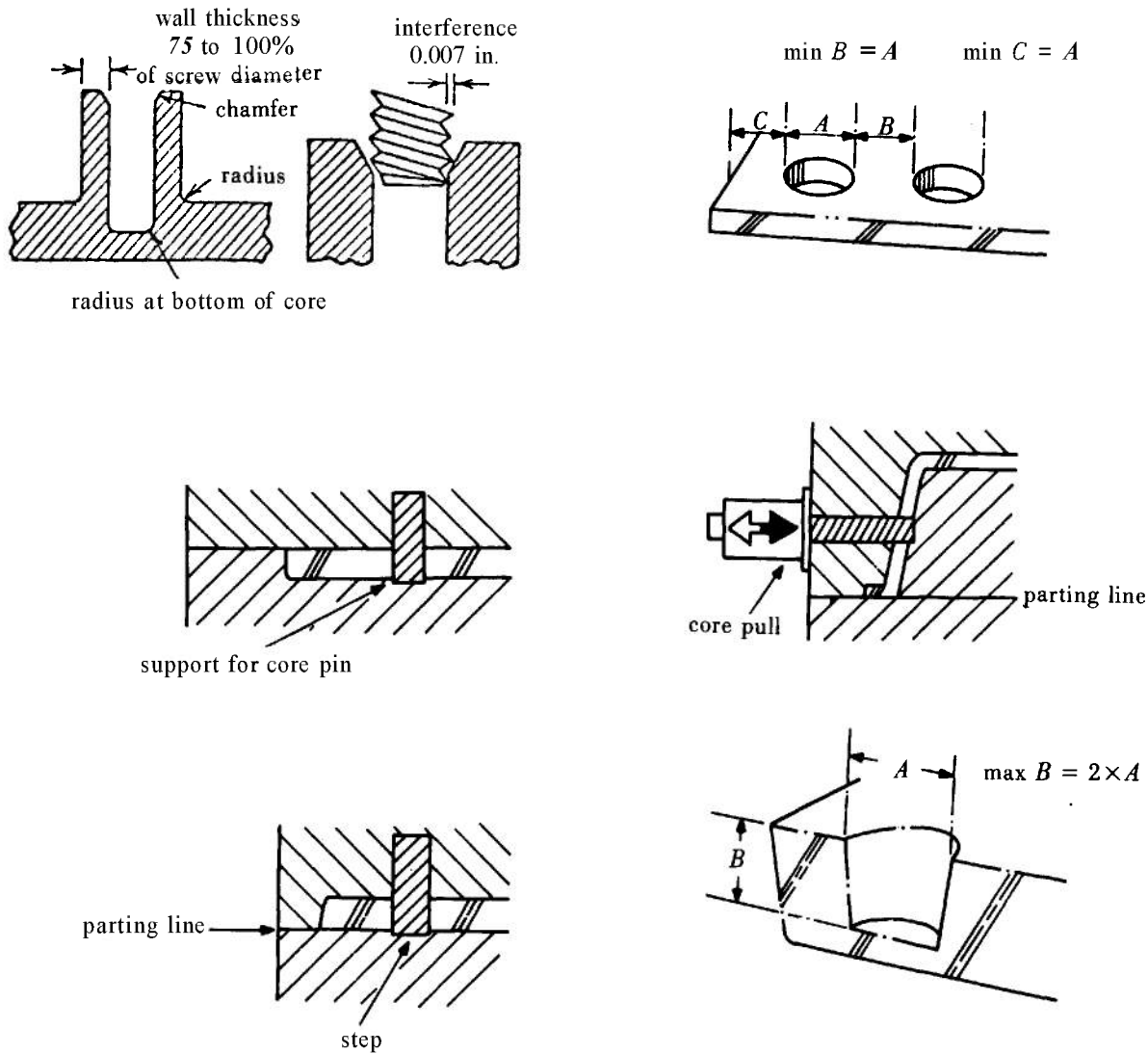
Fig. 6-8 shows the stress concentration is reduced 50% by increasing the ratio of radius to thickness from 0.1 to 0.6.

It is recommended that any inside corner radius be 25-75% of the adjacent wall. Minimum radius should be 0.005 in. for injected molded parts and 1/8 in. for hot-flow stamped items.

6-8 WALL THICKNESS

Parts should be designed with the minimum wall thickness that will provide the required structure. Also, walls should be kept as uniform as possible. Any wall variation should blend as gradually as possible. Where considerable wall variations are required, it would be better to make several parts and assemble them. Thick and thin sections in the same part can result in voids, sinks, and warpage.

Thin walls will fill better even though GRTP solidify more quickly. The glass fibers hold sufficient heat to achieve even flow into these areas in addition to the higher molding temperature and pressure used. Depending on the material selected, the wall thickness can be 10-50% less than those of unreinforced material. Nominal wall thickness for GRTP is 0.100-0.180 in. with 0.050 in. the average minimum and 0.500 in. the average maximum thickness.



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Figure 6-7. Design of Holes^{2,4}

The optimum wall thickness for nylon-, polycarbonate-, and styrene-based materials is about 1/8 in.; polyolefins are about 50% heavier. The minimum wall thickness is about 0.018-0.020 in. for polycarbonate-, polyester-, and styrene-based material.

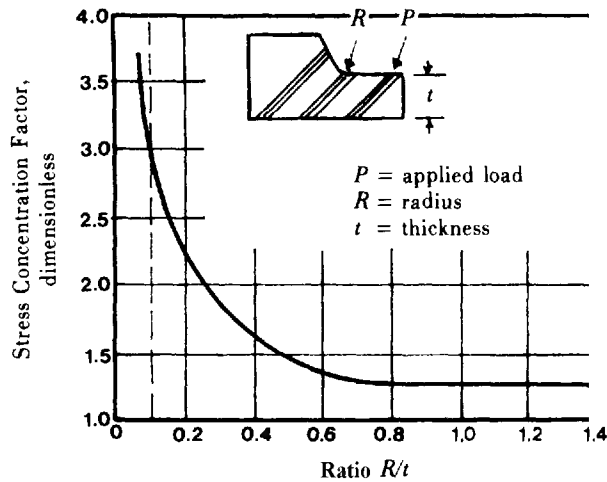
By designing hollow ribs, bosses, and elevation changes, the designer can achieve intricate part geometry while maintaining nominal thickness throughout the part. This will minimize warpage, save molding material, and cycle time.

Fig. 6-9 illustrates some methods for maintaining uniform wall thickness.

6-9 WELD AND PARTING LINES

A parting line is a mesh on a molded piece where the sections of the mold meet in closure. Parting lines should be designed in an inconspicuous edge of a part to improve appearance and minimize finishing operations.

A weld line is created by the fusion of material as it flows around an obstruction in the mold. Weld lines should be designed to avoid areas of high stress concentration. Weld line strength is increased with increasing stock temperature and decreasing injection pressure but is relatively



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Figure 6-8. Stress Concentration vs Radius-Thickness Ratio⁴

unaffected by mold temperature⁵. Table 6-1 shows the weld line properties of 30% and 20% glass-reinforced polystyrene and polyethylene. The 20% glass-reinforced resins have a greater weld strength when measured in flexure using doubly end-grated ASTM-D-1822 type S specimens.

6-10 INSERTS (see also par. 5-7.3)

Inserts of steel, brass, and aluminum have been found satisfactory when the following guidelines are applied:

TABLE 6-1. WELD LINE PROPERTIES¹

Base Resin	Glass Content, wt %	Melt Temperature °F	Mold Temperature °F	Weld Line Strength, psi
Polystyrene	30	450	150	6,500
Polystyrene	20	450	150	8,300
Polyethylene	30	320	100	3,909
Polyethylene	30	420	100	4,225
Polyethylene	30	420	150	4,500
Polyethylene	20	420	150	4,700

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1. Inserts should be located perpendicularly to parting lines and secured so they will not be displaced during material flow under pressure.

2. Pin supported inserts require a hole diameter of 1/8 in.

3. Inserts less than 1/4 in. diameter require a boss diameter of at least two times the diameter of the insert.

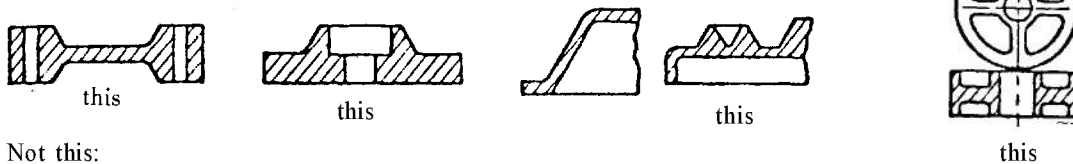
4. Use an insert with a coarse knurl for maximum holding power. The knurl should end below the surface of the plastic.

5. Radius all sharp corners on the insert. Sharp corners on the knurl should be broken by tumbling or grit blasting.

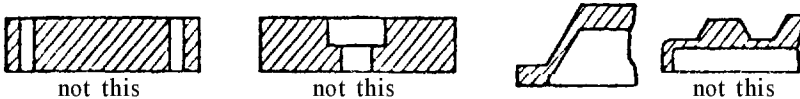
6. Inserts should have blind internal holes as opposed to through holes and have a generous radius or spherical shape at the closed end.

7. The open end of the insert should project above the surface of the molding.

Design this:



Not this:



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Figure 6-9. Wall Thickness⁴

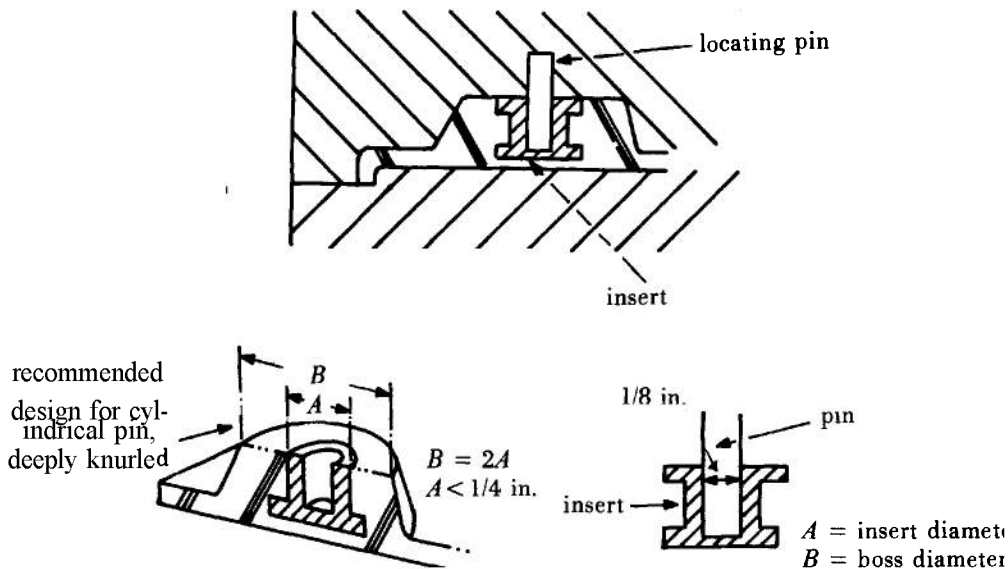
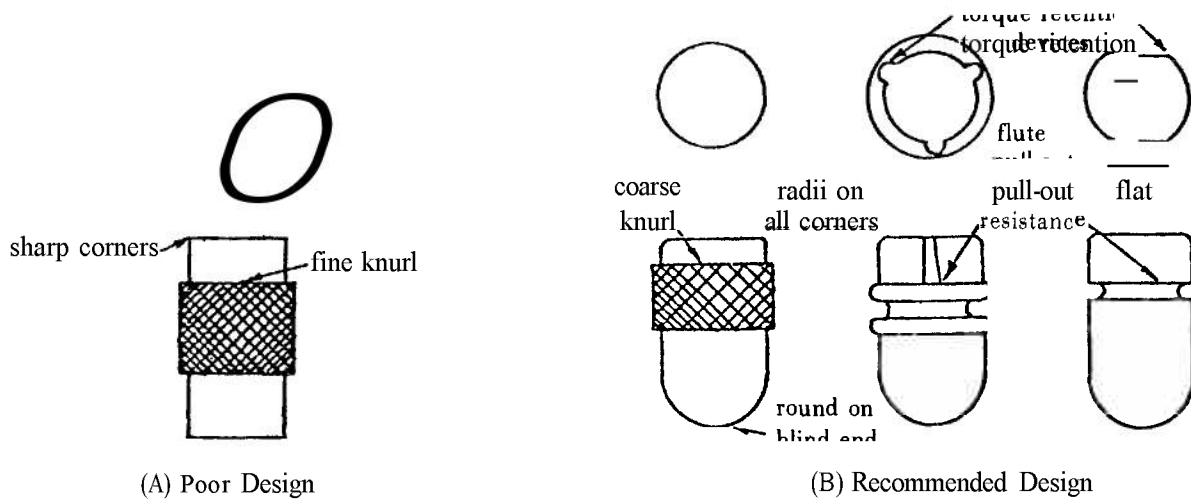
8. Inserts should be at room temperature when molded.

9. Wall thickness around the insert should be no less than half the insert OD.

Fig. 6-10 illustrates design parameters for molded-in inserts.

6-11 JOINT DESIGN

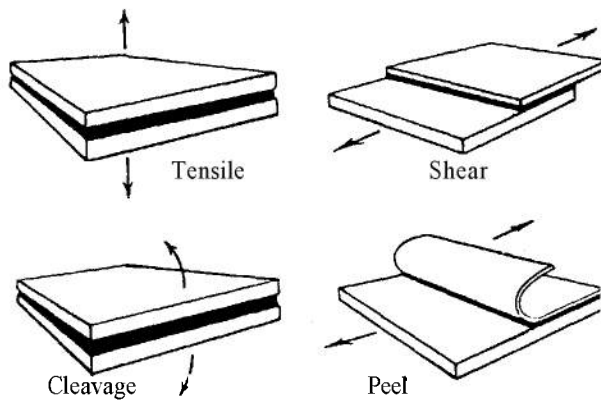
Joint design should be considered early in the design of parts. Proper joint design should create a bonding area which carries the load equally, placing the major stresses in shear or tension to



(C) Design of Molded-In Pin Inserts

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Figure 6-10. Design of Molded-In Inserts^{2, 4}



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Figure 6-11. Four Basic Types of Stress Encountered in Structural Bonding (Greatest strength is obtained when maximum area is used—as in tensile or shear loading).⁶

minimize cleavage and peel stresses as shown in Fig. 6-11.

In a tensile-loaded joint, forces are perpendicular to the plane of the joint. In a shear-loaded joint, forces are parallel to the plane of the joint. In both cases, stresses are distributed uniformly over the entire bonded area. By contrast, cleavage and peel stresses are concentrated on small sections of the bonded joints. Only a fraction of the total bonded area contributes to bond strength.

Because joints are subjected to a combination of several stresses, correct joint design is very important. Some recommended joint designs for various bonding methods are given in the paragraphs that follow.

6-11.1 ADHESIVE- AND SOLVENT-CEMENTED JOINTS

Fig. 6-12 depicts the typical joints used in adhesive and solvent bonding. Lap joints are generally used for adhesive bonding while butt joints are used for solvent cementing. For optimum strength, a combination of these designs is suggested since the lap joint is in shear while the butt joint is in tension. Both types of joints can be designed to bring the loads on the bonded parts in line.

Bonded areas and edges may be tapered or beveled to improve the length-to-thickness ratio, the

peel stress resistance, rigidity, and resistance to cleavage stresses.

Although the joggle lap joint allows shear stresses to be in the same plane as the bonded parts, it does not combine tensile and shear stresses in line with adherends. The double-butt lap joint, the recessed and landed-scarf joint, and the tongue-and-groove butt joint combine both types of stresses in line and, therefore, are recommended⁷.

Tapered butt joints and double scarf-lap joints also permit bonding and provide maximum tensile and shear strength. Overlap joints are recommended for bonding cylindrical parts⁷.

The right-angle butt joint is not recommended for corners because it produces either cleavage or peel stresses. Typical designs for adhesive bonding corners are slip and right-angle support joints. For rigid corner joints, an end lap, mortise and tenon, and mitered joint with spline can be used.

6-11.2 ULTRASONIC BONDING

Proper joint design and correct wall thickness are required for good quality ultrasonic welds. Figs. 6-13 and 6-14 illustrate some of the joint designs used.

In designing joints for ultrasonic bonding the following suggestions are made⁷:

1. Provide a small initial contact area such as a V-bead to concentrate the energy for amorphous materials.
2. Design the female part slightly larger.
3. Allow for the flow of molten material.
4. Allow for a slight dimensional change.
5. Locate the joint as close as possible to the point where the ultrasonic tool can be applied.
6. Provide a suitable horn contact area.
7. Provide locating pins or tongue and grooves for part alignment.
8. Provide proper proportioning of joint elements—avoid tight joints and large mating surfaces.

Energy director joint design is not generally recommended for the more crystalline materials; the scarf joint is preferred. Shear bead joints do not usually offer high strength but are satisfactory where hermeticity is required. The interference joints are successful where a slight warp-age is present which would prevent the full contact area of a scarf joint.

Wall thickness should be at least 0.020 in. Thin-

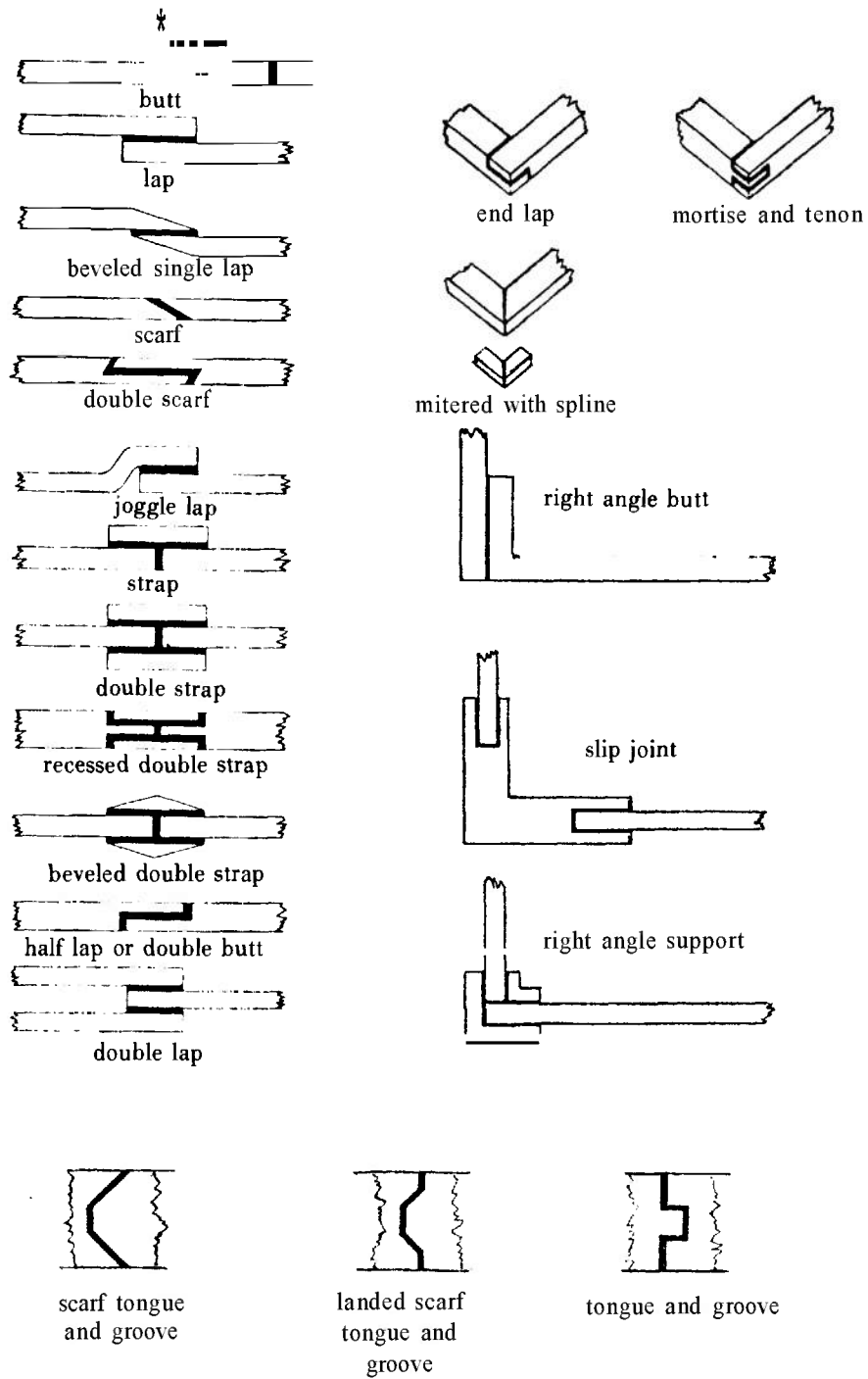


Figure 6-12. Adhesive and Solvent Cemented Joint Design

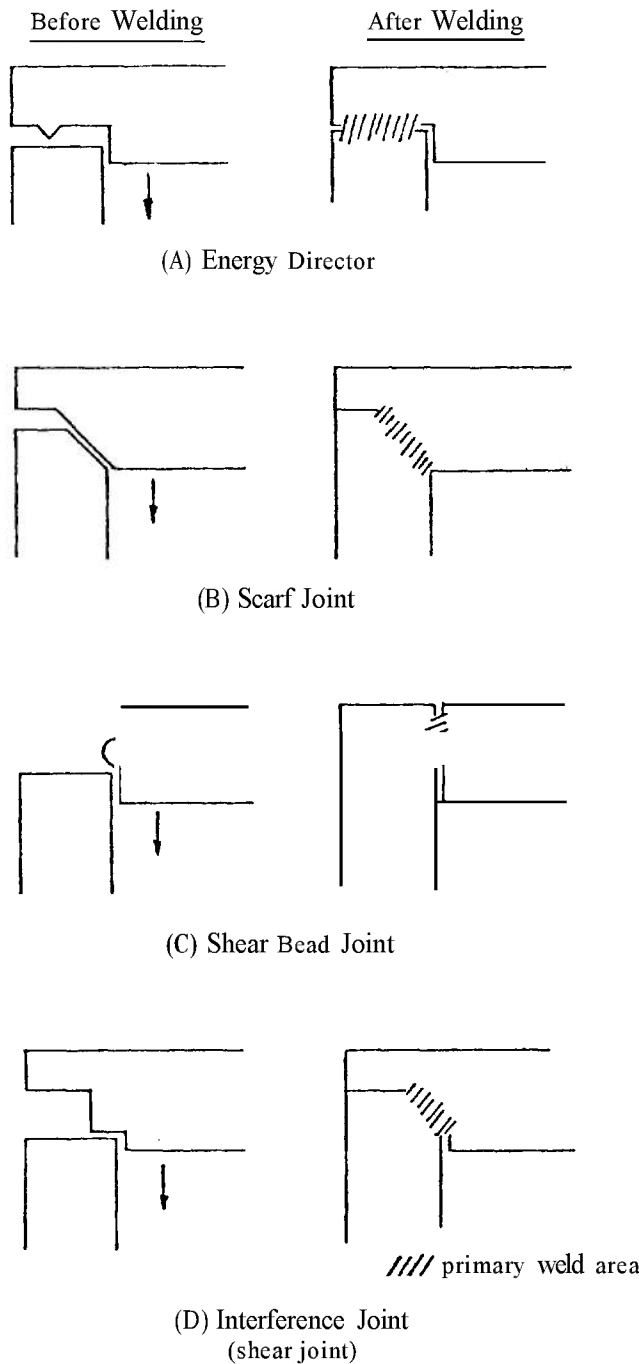


Figure 6-13. Ultrasonic Joint Designs of Crystalline GRTP's²

ner walls could concentrate the vibrations at the horn tip and cause melting⁷.

6-11.3 ULTRASONIC STAKING

The tip design of the ultrasonic horn will de-

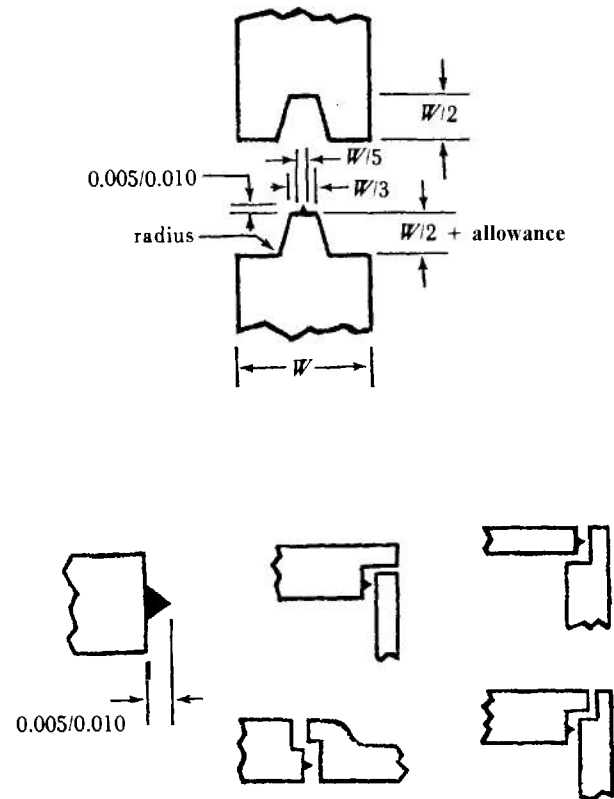


Figure 6-14. Ultrasonic Joint Designs for Amorphous GRTP's⁷

pend upon the application and the design of the stud. Some tip designs are shown in Figs. 6-15 and 6-16.

6-11.4 SPIN WELDING

In spin welding the joint configuration is limited to circular weld areas. Also, the edges to be welded should not have deeply grooved sections. A shallow tongue and groove or ledge which facilitates alignment but allows contact of all surfaces is preferred. Also a completely flat surface is acceptable but this requires precise alignment of tools and fixtures. Fig. 6-17 shows some of the recommended designs.

6-11.5 VIBRATION BONDING

The basic joint in vibration bonding is a butt joint as shown, before and after welding, in Fig. 6-18 (A). Unless parts have thick walls, a flange is generally required to provide sufficient rigidity and welding surface. Since there is some displacement of melt out of the joint, various types of

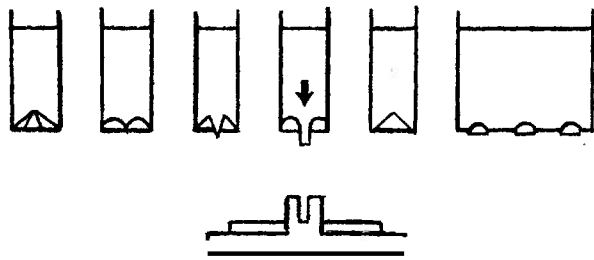
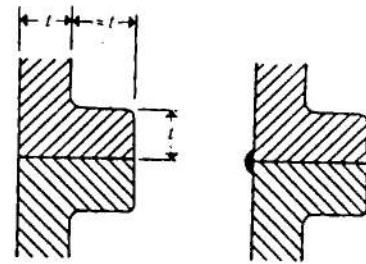


Figure 6-15. Tip Design for Ultrasonic Staking⁷



(A) Butt Joint

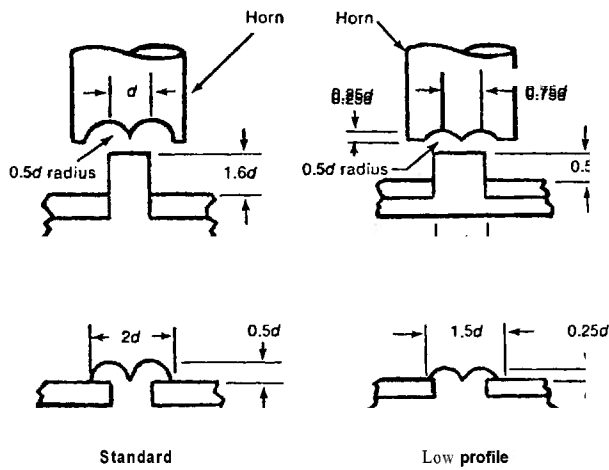
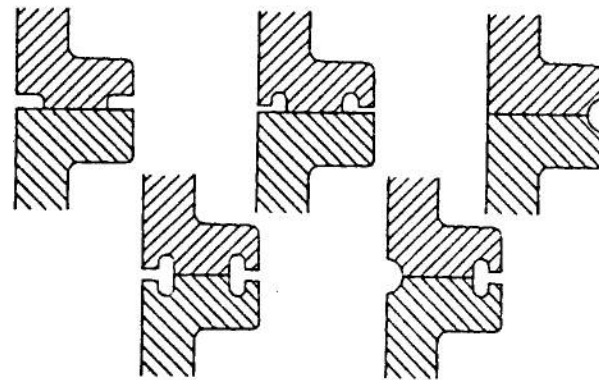
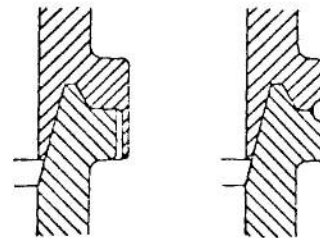


Figure 6-16. Standard and Low-Profile Staked Head-Forms⁷



(B) Butt Joint With Melt Traps



(C) Tongue-and-Groove Joint With Melt Traps

Figure 6-18. Vibration Bonding Joints⁷

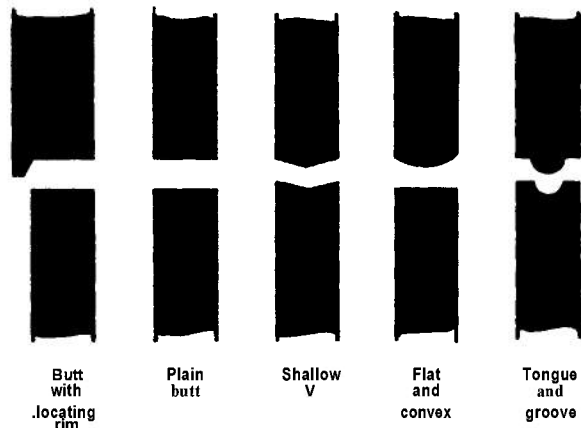


Figure 6-17. Joint Shapes for Spin Welding⁷

melt traps have been developed (shown in Fig. 6-18(B)). For circular parts, angular welding tongue-and-groove joints with traps, as shown in Figure 6-18(C), are recommended for the best results.

6-12 THREADS

Internal and external threads can be fabricated in GRTP parts either by molding or machining.

Machining generally is recommended for threads below 1/4in. diameter. Larger internal threads may be formed by a threaded core pin which is unscrewed either manually or automatically. External threads may be formed in the mold by splitting the thread along its axis or by unscrewing the part from the mold. When a parting line or the slightest flash on the threads cannot be tolerated, the second method (unscrewing the part from the mold) must be used (see Fig. 6-19). Mold designs with automatic unscrewing operations are also feasible.

Because coarse threads can be molded easier than fine threads, they are preferable. Generally, threads finer than 28 pitch or closer than class 2 should not be specified. The roots and crests of all type threads should be rounded with a 0.005-0.010 in. radius to reduce stress concentration and provide increased strength. Chamfers are also recommended.

6-13 SURFACE AND FINISHES (see also par. 4-8)

Many different textured surface finishes can be produced in GRTP parts by the mold cavity. Textures applied to surfaces opposite projecting ribs and bosses can disguise "sinks", surface depressions, or discolorations in pigmented parts. Molded-in styling lines or changes of contour are also effective in masking surface depressions.

High gloss surfaces can only be produced from highly polished molds. Also, careful design of ribs and bosses, plus the gating location in the mold, will help to minimize localized surface depressions and flow lines around inserts and pins in the mold. When high-gloss surfaces are required, "low shrink" resin systems should be used. Num-

bers, letters, and symbols can be molded into the part. Such symbols can also be hot-stamped. Characters should be smooth and rounded. They should be positioned on surfaces parallel to the parting line; otherwise, movable mold inserts are required.

6-14 STRUCTURAL ANALYSIS AND SAFETY FACTOR

When designing a new component, a theoretical stress analysis may be required. Generally, the same elastic design equations used for non-reinforced thermoplastics can be used for structural analysis of a GRTP.

When applying a mathematical stress analysis to a new design, a Factor of Safety (FS) must be considered. Based on various types of loading, the minimum FS for GRTP are⁴:

1. Static short-term loads, FS = 2, minimum
2. Static long-term loads, FS = 4, minimum
3. Variable or changing loads, FS = 4, minimum
4. Repeated loads, FS = 5, minimum
5. Fatigue or load reversal, FS = 5, minimum
6. Impact loads, FS = 10, minimum.

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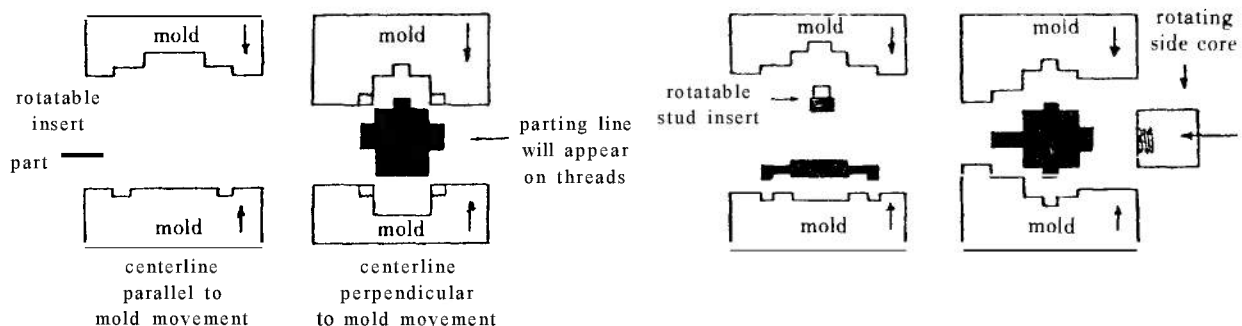


Figure 6-19. Thread Molding GRTP Parts'

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CHAPTER 7

MOLD DESIGN

Molds play an important role in the fabrication of GRTP parts. Accordingly, the design and construction of molds and their components are covered. Injection and stamping molds are considered.

7-1 INTRODUCTION

One of the most critical steps in the production of a GRTP part is the design and construction of the mold. It contributes more to the production efficiency and profitability of a molded product than any other element.

The development of a proper mold begins with the part design; molding material system selected; production volume; and part size, shape, and surface appearance as well as fabrication technique.

The paragraphs that follow discuss the mold design of the two most popular fabrication techniques— injection molding and stamping. Rotational molding is covered in the Engineering Design Handbook, AMCP 706-312, *Rotational Molding of Plastic Powders*. Not enough experience has been gained as of this writing to make specific recommendations on the other available techniques.

7-2 INJECTION MOLDS

7-2.1 MOLD MATERIALS

Injection molds usually are constructed of steel for production runs, and the use of standard mold bases (steel parts which contain the cavities and cores) is recommended. A number of companies supply standard mold bases and parts. These can be less expensive and superior to those made by the mold maker due to high volume and specialized equipment.

There are several types of steel available for the mold base, cores, cavities, and other molding surfaces and parts. The selection of the proper steel is based on many considerations such as frictional wear, compression forces, complexity of the core cavity shape, molding temperatures, and corrosive conditions. For most GRTP parts, a harder steel (up to 350 BHN) is recommended to increase tool life. When molding resins with a high loading of molybdenum disulfide, a low sulfur- and low phosphorous-containing steel is suggested for the cavity inserts'.

Cores and cavities are often polished and chrome plated to obtain a glossy surface appearance and in some instances to facilitate ejection. Chrome plating is also used with corrosive resin molding systems such as polyvinyl chloride. Stainless steel molds have also been used successfully and should not be overlooked'. Cast beryllium-copper may be used for production cavities but should be flash-chromed to prevent surface staining with some resin systems, e.g., polycarbonate.

The most important properties besides uniform structure and freedom from defects in selecting a steel for molds are compressive strength, hardenability, machinability, stability in hardening, and polishability. In the majority of cases, it is possible to work with three basic types of mold steel, namely, AISI P20, AISI H13, and AISI 01.

As with unreinforced thermoplastics, aluminum Kirksite or epoxy molds are satisfactory for GRTP prototype work.

7-2.2 MOLD COMPONENTS

The major mold components are illustrated in Fig. 7-1 and described in the paragraphs that follow.

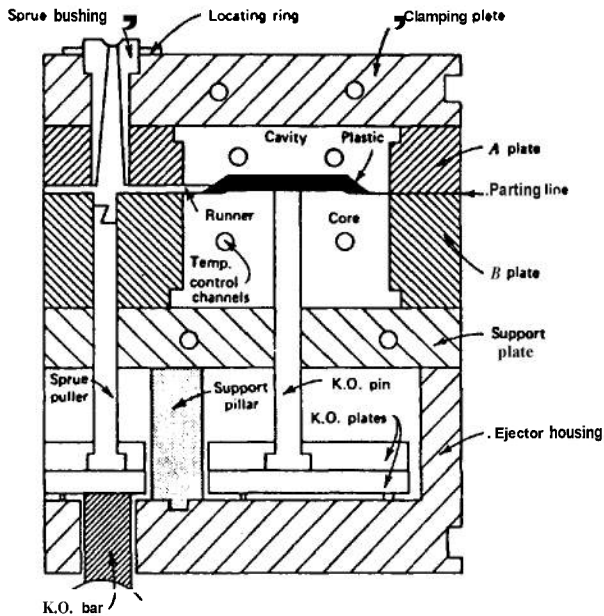
7-2.2.1 Cores and Cavities

The cores and cavities determine the configuration and surface appearance of the part. The cavity is the female section of the mold and determines the exterior portion of the part. The core is the male section of the mold and forms the inside portion of the part.

7-2.2.1.1 Core Pins

Core pins are used to fabricate small holes or cored-out sections of the part. They are used instead of machining which is more expensive and in GRTP parts would expose the glass fibers.

Side cores are used to form undercuts or holes perpendicular to the direction of the mold openings. They usually are mounted on the moving



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Figure 7-1. Schematic Drawing of a Two-Plate Mold (Robinson Plastics Corp.)²

half of the mold and extend into the part to form the hole or undercut. They are retracted by air, or hydraulic or mechanical cam action prior to ejection of the part. If the side cores are located on the stationary half of the mold, care must be taken to insure that they are retracted before the start of the mold opening to prevent mold damage.

The recommended core length for blind cores larger than 0.187 in. in diameter is 2.5 times the diameter. For blind cores smaller than 0.187 in. in diameter, the suggested core length is twice the diameter³.

The length of cored through-holes should not exceed six times the diameter for core diameters greater than 0.187 in., and four times the diameter for core diameters smaller than 0.187 in. Draft should be added to all cores³.

7-2.2.1.2 Collapsing Cores

Collapsing cores are used to fabricate internal and blind threaded holes. This type core is designed with separate wedge-shaped parts which collapse as the mold opens to disengage the molded threads. One disadvantage of these cores is the ability to cool the core section effectively.

7-2.2.2 Mold Plates

A mold consists of two to ten or more steel plates each of which performs a specific structural function. A description of the plates and their functions follows:

1. **Cavity and Core Plates.** These contain the individual cavities and cores. These can be separate assemblies mounted into their respective plates or machined directly into the plates themselves. The cavity plate usually has four leader pins which are guided into corresponding bushings in the core plate. Sometimes the positions of leader pins and bushings are reversed. The purpose of these pins is to align the plates, cavities, and cores. In critical applications a wedge locking device may be required on cavity and core plates. This can alleviate wear on the leader pin and bushing during molding. A stripper ring should not be used to align the cavity and core since the compression may lead to permanent deformation and cause wear and galling on the core.

2. **Top and Bottom Clamp Plates.** These are mounted directly to the press platen. They are used in multicavity molds to provide structural backing for the cores and cavities.

3. **Sleeve Plates.** These are located between the core and cavity plate. It can eject the part itself or contain a number of separately mounted sleeves as required in multicavity molds. Sleeves often are used for circular parts with an undercut in the core section or where core pins prohibit use of ejection pins. The sleeve surrounds the core in a flash free fit. When activated on the opening stroke of the press, the sleeve moves forward beyond the core, stripping the part from the mold. This requires a taper match between the sleeve and core generally about 3-10 deg per side to eliminate wear.

4. **Ejector Plates and Pins.** Ejector pins are countersunk into the ejector plate. The pins extend through the mold to the core or cavity molding surface. Pins are made from a high chrome vanadium or nitriding steel. The ejector plate also contains four push-back pins. These push the ejector plate to its back position when the mold closes so that the ejector pins and cavities are not damaged.

The ejector pins are activated by the movement of the ejector plate in conjunction with the knockout system of the press. As the mold opens the ejector plate pushes the ejector pins forward, pushing them through the mold and forcing the

part from the core or cavity. Ejector pins should be located on ribs, bosses, etc., to provide positive ejection. They should be designed so the part is pushed out rather than pulled out of the mold. Because GRTP are not as resilient as unreinforced resins, more knockout pins should be used. A general rule of thumb is to place pins at about 1-in. intervals. They also should be designed with sufficient contact and to prevent overcompressing the part contacting the pins.

A sprue puller pin is attached to the ejector plate, directly opposite the sprue. An undercut (Z-shaped) or reverse taper is designed on the sprue puller so that GRTP material will mold around it. When the ejector plate moves forward, the pin is raised above the mold surface so that the runner can slide off the undercut.

Threaded parts can be removed from the mold manually, using threaded inserts, by collapsing cores or automatic unscrewing devices. With threaded inserts, the part is ejected from the mold with the insert intact. The insert is then removed. Usually two inserts are used to decrease production time—while one set is being removed, the other is being used in molding.

Molds can also employ automatic devices to free a threaded part via either a pneumatically or hydraulically activated rack and pinion.

5. Support Pillars and Plates. The support plate rests on the ejector housing and provides structural backing for the core. Support pillars are located between the parallels of the ejector housing and go through the ejection plate to provide additional support. They must be located without interfering with the ejection system and have sufficient area so that the clamp force of the machine will not hob the pillars into the support plate.

Insufficient mold support will result in flashing, ejection problems, parts scoring, and cracking.

7-2.2.3 Seating Ring and Sprue Bushing

The seating ring centers the sprue bushing on the injection platen of the machine directly in line with the nozzle of the injection cylinder. The sprue bushing should be as short as possible from the nozzle to the parting line of the mold and have a taper of at least 3 deg in order to maintain the heat of the melt. Cold slug wells should be used wherever possible to permit the leading cold resin to be trapped and to permit the hot resin to

enter the runner and cavity. Sprue slug wells should be designed with a back taper for pulling the part. Ring or Z-pullers are not recommended since GRTP tend to shear in undercuts of this type.

It is suggested that the radius where the sprue bushing meets the nozzle be 1/8-1/4 in. greater than the radius of the nozzle. This provides a contact line rather than a broad surface, which is helpful when stray glass fibers get between the surfaces⁴.

7-2.2.4 Runner Systems

7-2.2.4.1 Conventional Runners

The runner is the connection between the sprue and the gate transporting the GRTP melt. Runners for GRTP should be large, full round, and well polished. Where this design is not possible, trapezoidal runners are considered next best. Depth should be almost equal to width. Runners should be as short as possible. This maintains a flow area in the center of the diameter since reinforced resins tend to solidify at the walls of the runner. If long runners are required, the main runner should bypass the cavity, thus leaving a cold slug at the end. A short branch runner off the main runner will allow the hot compound to flow into the cavity and with no cold material restriction. Fig. 7-2 presents some recommended runner diameters. A diameter of 1/4-3/8 in. is suggested for the majority of parts. Right angles should be avoided. Specific recommendations for glass-reinforced acetal copolymer, polyester, and nylon 6/6 are given in Tables 7-1 and 7-2.

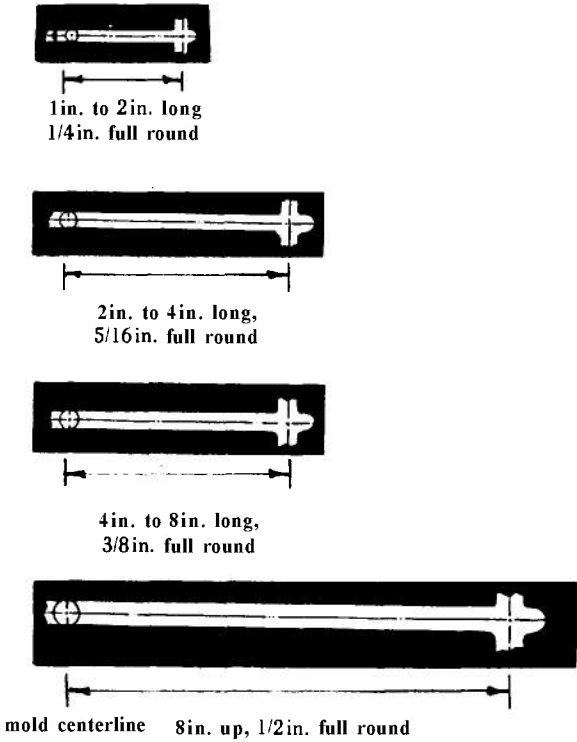
If runners are not round, the cross-sectional areas should be no less than those recommended for the full-round runner for these resin systems.

In multicavity molds where close part tolerances are required, a balanced runner system is extremely important to achieve part-to-part uniformity. Fig. 7-3 depicts some multicavity runner systems.

7-2.2.4.2 Hot Runner Molds

In a hot runner mold, the runner is contained in a manifold which has electrical heating cartridges. The heated runner keeps the GRTP in a fluid condition (Fig. 7-4).

The manifold normally is insulated by air gaps to keep the mold frame cool. An advantage of hot



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Figure 7-2. Recommended Runner Sizes⁵

TABLE 7-1. RUNNER SIZE RECOMMENDATIONS FOR GLASS-REINFORCED ACETAL COPOLYMER AND POLYESTER⁷

Part Thickness, in.	Runner length, in.	Minimum Diameter, in.	
		Acetal Copolymer	Polyester
0.020 · 0.060	< 2	3/16	1/16
0.020 · 0.060	> 2	1/4	1/8
0.060 · 0.150	< 4	1/4	1/8
0.060 · 0.150	> 4	1/4	3/16
0.150 · 0.250	< 4	5/16	1/4
0.150 · 0.250	> 4	3/8	

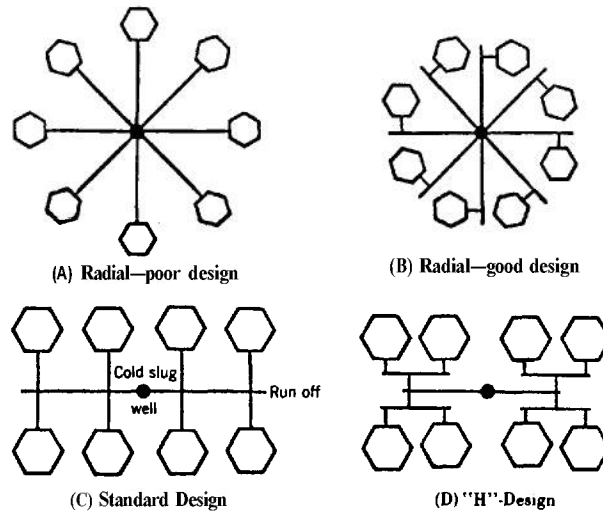
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runner molds over the insulated runner type is that the possibility of the GRTP in the runner solidifying during an interrupted cycle is minimized due to the added electrical heat provided. Hot runner molds are more efficient for relatively small parts where production requirements de-

TABLE 7-2. RUNNER SIZE RECOMMENDATIONS FOR GLASS-REINFORCED NYLON 6/6⁵

Part Thickness, in.	Runner Length, in.	Minimum Diameter, in.
0.025 · 0.050	< 2	0.060
0.025 · 0.050	> 2	0.125
0.100 · 0.150	< 4	0.125
0.100 · 0.150	> 4	0.187
0.150 · 0.200	< 4	0.187
0.150 · 0.200	> 4	0.250

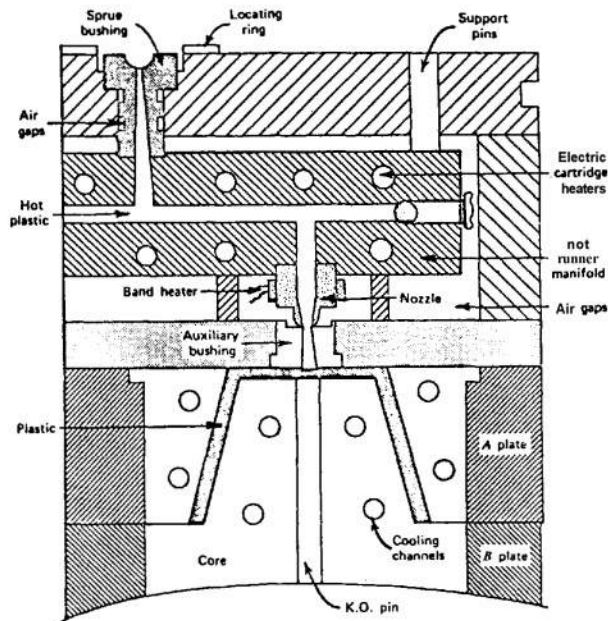
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Figure 7-3. Runner Systems²

mand a large number of cavities. There is also the obvious advantage of no sprues or runners to grind. However, there are problems of temperature control, gating, balanced flow, drooling, and freezing. If the nozzle is too hot, it will drool; if it is too cool, it will freeze. Also, hot runner molds are susceptible to contaminants clogging the nozzle and gates. The time required to clear clogged gates due to contaminants in the material can be lengthy — it may require 4-12 h downtime to dismantle the mold and remove the foreign particles. One of the most important developments in hot runner molds is the internally heated bushing. These can be used as a long sprue bushing or as



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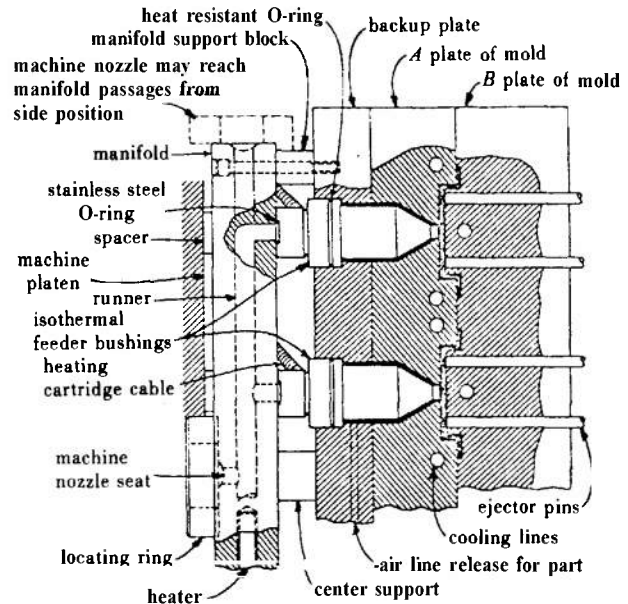
Figure 7-4. Schematic Drawing of a Hot Runner Mold (Robinson Plastics Corp.)²

an individual nozzle gate in a multiple-cavity system. They are referred to as isothermal bushings because their heated internal shank can maintain the plastic inside at essentially constant temperature. A layer of heated plastic insulates the hot shank from the heater body and from the remainder of the mold. This allows the end face of the bushing to be maintained at or near the temperature of the mold cavity, of which it is a part. The configuration of the tip of the heated shank is such that the plastic is kept at flow temperature despite the fact that the face of the heater body is relatively cool⁶.

Fig. 7-5 shows an arrangement of multiple isothermal nozzles in a mold. The manifold is bolted to the mold backup plate to clamp the bushings in place. In this style of mold, the cartridge heaters in the manifold body are controlled by thermocouples inserted into the manifold. Temperature of the feeder bushings usually is controlled by variable voltage controllers⁶.

7-2.2.4.3 Insulated Runner Molds

In the insulated runner mold no heat is added to the runner. The outer circumference of the run-



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Figure 7-5. Multiple Isothermal Bushings in a Hot Manifold Mold'

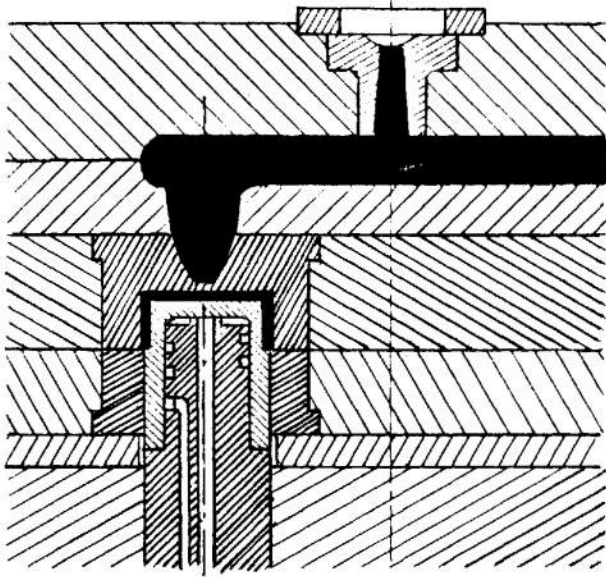
ner solidifies while the interior remains fluid in preparation for the next shot. The runner system is heated by the molding compound which is heated in the injection cylinder. As shown in Fig. 7-6, this requires wide diameter runners and sprues.

The runners are usually about 1 in. in diameter and the sprues large enough to accommodate a probe or torpedo. The width of the runner is critical. If it is too wide, considerable clamping pressure is necessary to prevent flashing. If it is too narrow, the melt is likely to freeze up and solidify.

Heated probes (Fig. 7-7) are usually added at the gate to sustain better flow through the gate.

In this type of insulated runner mold design, the runner plate and cavity plate are bolted together and are only opened to remove the solidified runner after breaks in the molding cycle or to remove freeze-ups.

The probe or torpedo is heated by a cartridge which must supply heat continuously. Where more than one probe is used, each must be wired to its own control to insure the fine control necessary to maintain the balance between freeze-off and drooling at the gate.



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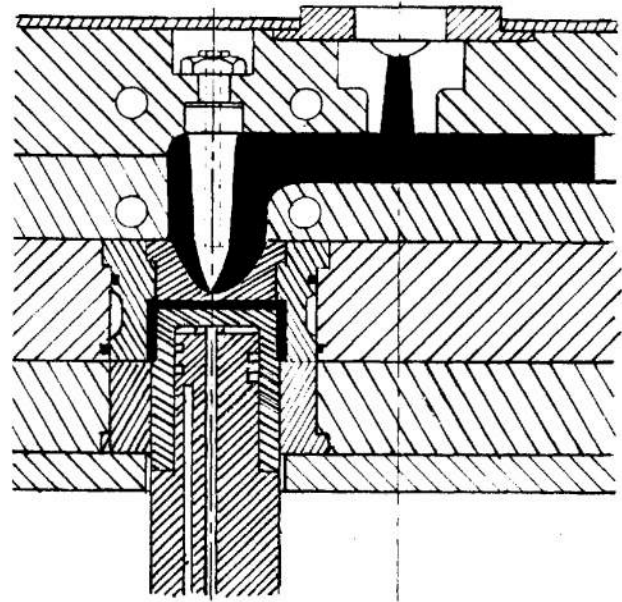
Figure 7-6. Runnerless Mold in Which No Additional Heat Is Supplied to Runner (Wide diameter insulated runner allows the outer circumference of the melt to solidify against runner walls while the central core remains molten in preparation for the next shot.)⁷

The advantages and disadvantages of these insulated runner mold designs are similar to the hot runner. They permit elimination of the runner and subsequent reduction of scrap, regrind, and production cycles. However, the gate area is subject to clogging by foreign particles, and short interruptions in the cycle can freeze up the runner. The insulated runner molds also require careful temperature control to maintain the balance between freeze-up and drooling.

7-2.2.5 Gates

The gate is the connection between the runner and the molded part. Gate size and geometry depend upon the material system, mold layout, and part design. Proper gating is one of the most important factors in achieving a good molded part. Fig. 7-8 shows some of the gating designs used in injection molding.

There are basically two types of gates: restricted (pinpointed) and large. Restricted gates are circular in cross section and usually do not exceed 0.060 in. in diameter. Large gates are usually



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Figure 7-7. Heated Probes Added at Gate of Runnerless Mold, Which Also Uses an Insulated Runner (Referred to as "runnerless" since no scrap runner is produced with part)⁷

square or rectangular and about 1/4 in. wide by 3/16 in. high².

Gate location should be selected carefully to minimize possible part distortion due to anisotropic shrinkage of GRTP. For best results, the gate should be located to achieve a balanced flow in all directions and a minimum flow length from the gate to the extremities of the part. When this is not possible, the gate should be located so that the flow direction is along the axis of the most critical dimension since the mold shrinkage is considerably less in the direction of flow.

The correct way to provide longitudinal flow for rectangular or circular parts is shown in Fig. 7-9. Other types of gating can be used to achieve uniform flow in center cored circular parts as shown in Fig. 7-10. However, the large degree of anisotropy in GRTP can cause out-of-roundness warpage with these gate locations. Therefore, it is recommended that wherever possible full ring gating (or full disc gating) be used.

Fig. 7-11 illustrates the orientation patterns developed by four-point gating with GRTP in circular and cylindrical shapes.

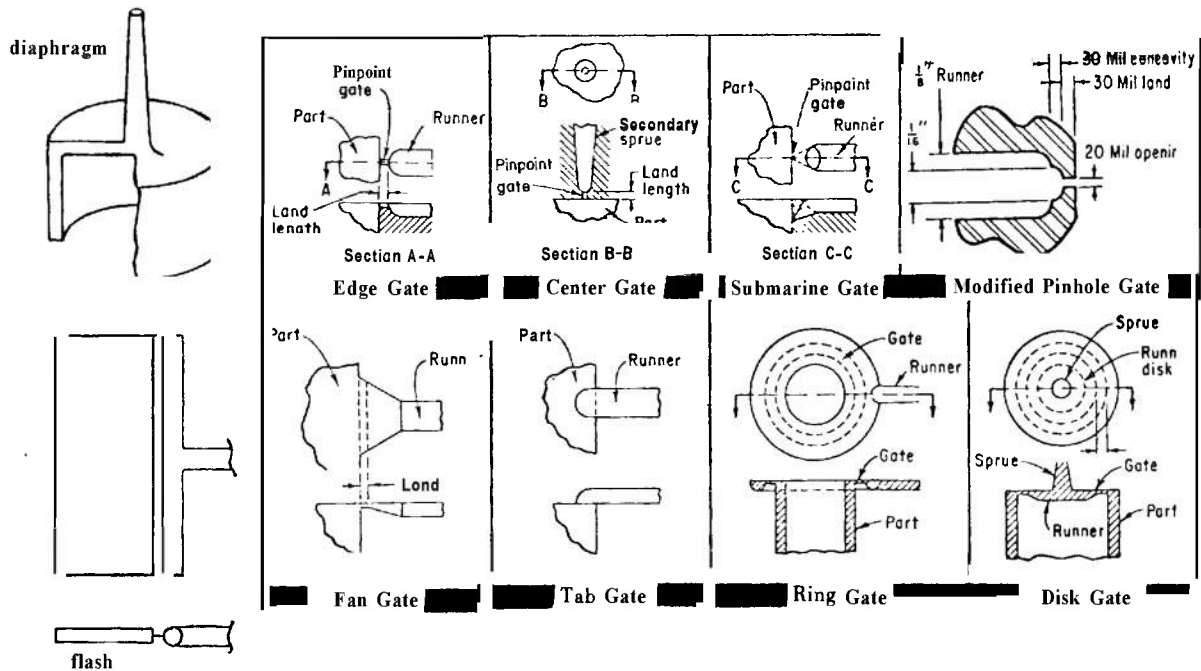
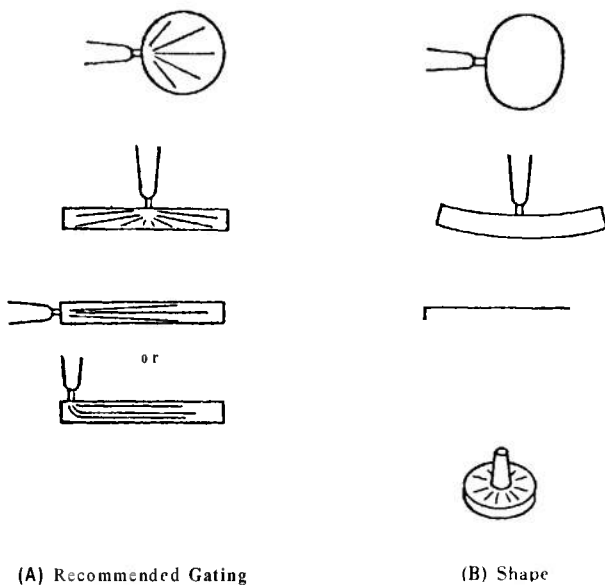


Figure 7-8. The Most Popular Types of Gating Systems Used in Injection Molding Process'



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Figure 7-9. Gating Used in Rectangular and Circular Parts⁸

It is also recommended to gate into the thickest section of the part to avoid sinks or voids. However, if surface finish is critical on a thin section, the gate should open into that section to maximize gloss. Also, gates should be back tapered into the runner so that the melt is not directed against a cavity wall or core pin (see Fig. 7-12). This is to minimize glass fiber breakage and the resulting decrease in physical properties. Gates should not be located in part areas subjected to high stress levels, fatigue, or impact.

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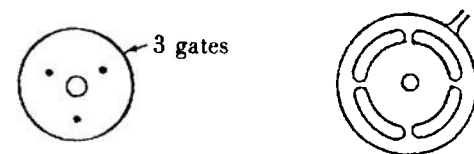
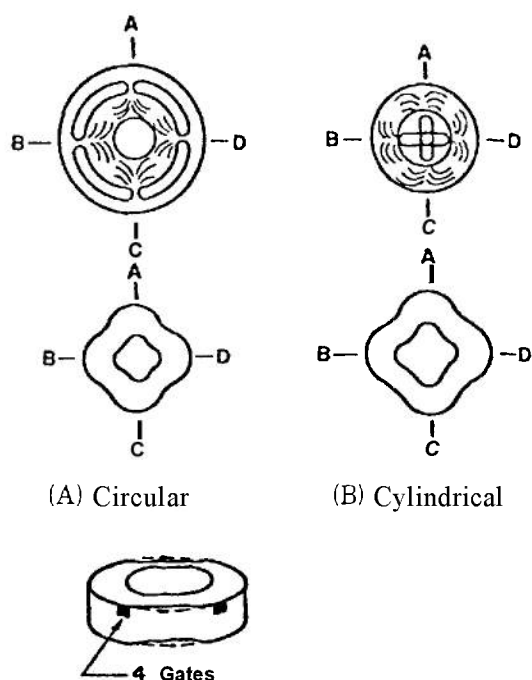


Figure 7-10. Gating for Circular Parts'



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Figure 7-11. Orientation Patterns in Four-Point Gating of Circular and Cylindrical Shapes¹

To avoid weld lines and localized part weakness, the number of gates should be kept to the absolute minimum necessary to fill the part. If more filling capacity is required, the gate should be enlarged instead of adding more gates¹.

Round or rectangular gates are the most widely used. Their size should be from two-thirds to the full width of the cavity wall. Some recommended

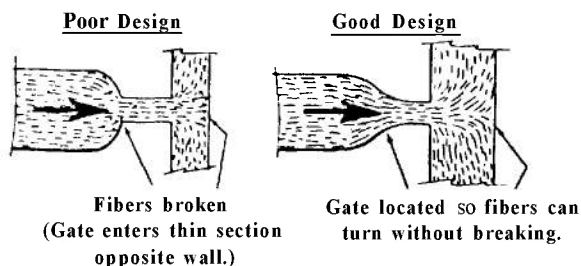


Figure 7-12. Gate and Mold Design Affect Part Strength⁹

gate sizes for glass-reinforced polyester, acetal copolymer, and nylon 6/6 are given in Tables 7-3 and 7-4.

Small pinhole gates should be avoided. A round gate should not be less than 0.040 in. in diameter. The larger the part, the larger the size gate required up to a maximum of the part wall thickness.

Land lengths should be short (0.020-0.040 in.) to keep the pressure drop through the gates to a minimum to control shrinkage.

Other gate designs such as diaphragm, flash, or submarine can be used in special applications. For example, submarine gates which can be used in several GRTP systems require that the approach to the gate be designed with a relatively wide angle as shown in Fig. 7-13. The most widely used gating in hot runnerless molding are the straight-through gate and the ring gate shown in Fig. 7-14.

The straight-through gate is a simple inexpensive way of gating that can accommodate probe or torpedo shifts resulting from heat expansion of the manifold. Gate temperature control is poor

TABLE 7-3. GATE SIZE RECOMMENDATIONS FOR USE WITH GLASS-REINFORCED THERMOPLASTIC POLYESTER AND ACETAL COPOLYMER⁵

Gate Type	Part Thickness, in.	Gate Dimensions, in.		
		Depth	Width	Land Length
Edge, rectangular	0.030-0.090	0.020-0.060	0.020-0.090	0.040
	0.090-0.125	0.060-0.085	0.090-0.130	0.040
	0.125-0.250	0.085-0.165	0.130-0.205	0.040
Direct, full round, from secondary sprue	Less than 0.125	0.030-0.050"		0.040
	0.125-0.250	0.040-0.120"		0.040

"Gate diameter.

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TABLE 7-4. GATE SIZE RECOMMENDATIONS FOR GLASS-REINFORCED NYLON 6/6⁵

Gate Type	Part Thickness, in.	Gate Dimensions, in.		
		Depth	Width	Land Length
Edge, rectangular	Less than 0.030	Up to 0.030	Up to 0.045	0.030-0.050
	0.030-0.125	0.050-0.080	0.050-0.080	0.030-0.050
	0.125-0.250	0.060-0.140	0.060-0.140	0.030-0.050
Direct, full round, from secondary sprue	Less than 0.125	0.030-0.050"		0.030-0.050
	0.125-0.250	0.040-0.120"		0.030-0.050

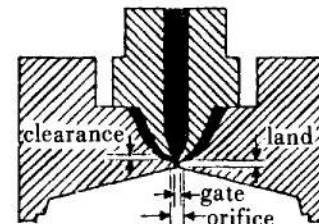
*Gate diameter.

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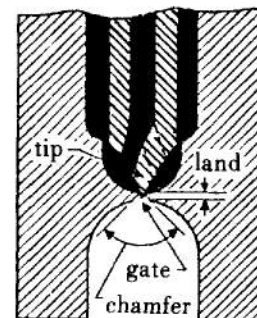
and the gate is prone to stringing with low melt-viscosity materials. Ring gating although more expensive provides good temperature control, minimum stringing, and clean gate break. Heat expansion of the torpedo must be considered since it can block the gate and affect filling. These designed gates are only applicable to top gating".

When side gating is required, the torpedo design must be changed. A side or edge gate is shown in Fig. 7-15. This is a straight-through gate perpendicular to the torpedo. The end of the torpedo forms a narrow slot slightly wider than and in line with the gate. This gate design produces clean gate shear superior to that of tunnel gates in cold runner molding".

The most sophisticated type of gate is valve-gating. It is used in both hot and cold runner molding. The principle of valve-gating is that the opening and closing of the gate is controlled by mechanical means such as hydraulic or pneumatic



(A) Straight-Through Gate With Inlet Orifice Larger Than Gate Diameter to Allow for Mold Expansion



(B) Ring Gate Which Has a Tip Protruding Into Gate to Form the Ring

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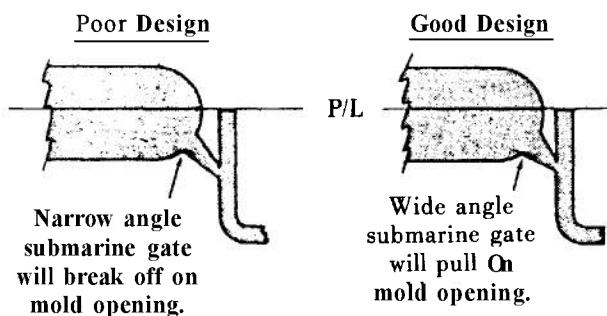
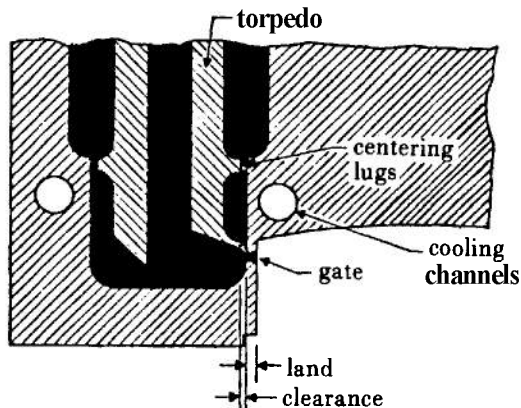


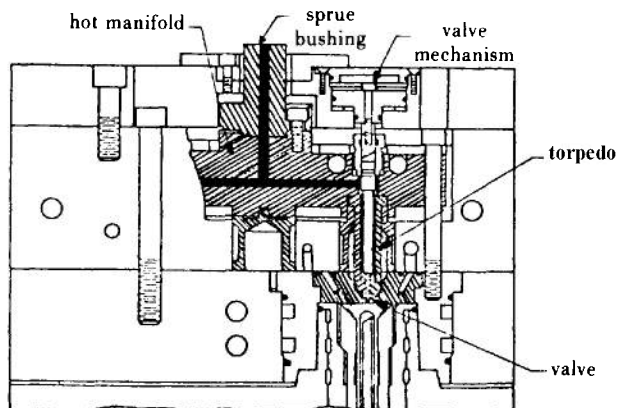
Figure 7-13. Submarine Gates Require Broad Taper⁸

Figure 7-14. Commonly Used Gating for Hot Manifold Molding"



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Figure 7-15. Suggested Design for Side or Edge Gating of a Hot Manifold Mold (Essentially a straight-through gate perpendicular to torpedo)"



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Figure 7-16. Partial Cross Section of a Hot Manifold Mold Equipped With a Mechanically Actuated Valve-Gating Mechanism"

pressure, cams, or springs. Fig. 7-16 illustrates a mechanically actuated valve-gate in a hot runner mold.

A high rate of melt precompression is obtainable with valve-gating. This facilitates molding thin wall parts at fast cycles to prevent the chilled cavity and core surfaces from freezing the material before the part is formed. Potential problems of valve-gating are the governing mechanisms and—in hot runner molds—thermal expansion, concentric guiding of the needle, and possible leakage between the needle and the manifold block.

7-2.2.6 Vents

It is important in molding GRTP that the mold be adequately vented to permit the release of trapped air. Trapped air can cause surface defects and scorching of parts. Good venting is also essential for rapid and uniform filling.

The location and size of vents are governed by experience. They must be located wherever air will be trapped due to resin flow, at weld lines, and end of cavities. Spacing should be about 1 in. apart along the mold parting lines.

Overflow pockets are suggested to remove trapped air and the cold leading edge of resin on the parting line. This type of vent shown in Fig. 7-17 has been found to equalize composite hardness to within a few points from one end to the other in long thin parts.

Other parting line vents (Fig. 7-18) should be ground with a taper from approximately 0.002-0.003 in. at the outside edge⁴.

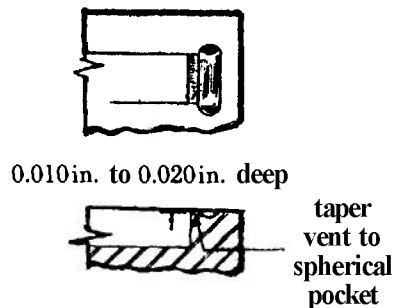


Figure 7-17. Overflow Vent or Puddle⁴

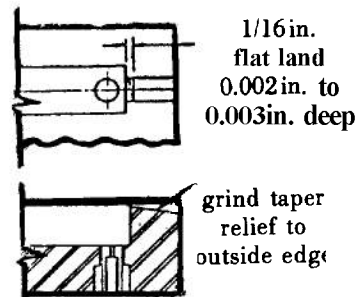


Figure 7-18. Parting Line Vent⁴

Vents 0.001 in. deep and 0.125 in. wide are recommended for low viscosity glass-reinforced systems such as nylon 6/6 and polyesters; 0.0015 in. deep by 0.125 in. wide for acetal; 0.002-0.004 in. by 0.250 in. wide for polycarbonate; and 0.004 in. by 0.200 in. wide for highly viscous resin such as polysulfone. Vents should be deepened, beginning 1/8 in. from the cavity³.

Self-cleaning vents can be located in the bottom of cavities by grinding flat surfaces 0.010-0.020 in. deep on the side of knockout pins, and cavity vents 0.002 in. deep as shown in Fig. 7-19. This self-cleaning type of vent can become clogged when mold release spray is used. If parts tend to burn, the knockout plate can be moved forward and the flats wiped clean.

7-2.2.7 Mold Cooling

Good mold temperature control is essential to successful molding. This can be achieved by combining good mold design and the judicious selection of mold materials with standard cooling techniques. For example, if two dissimilar metals are used in fabricating the cavity and core, the material with the lower thermal conductivity will retain the heat longer. Since beryllium-copper dissipates heat much more rapidly than tool steel, it might be desirable to hollow out the core and put in a beryllium-copper insert to improve its thermal conductivity.

Heat is removed from the plastic by conduction through the surfaces of the cavity and cores, and is absorbed by the mass of the cavity block, core, and entire frame of the mold. To facilitate this cooling, channels are drilled longitudinally

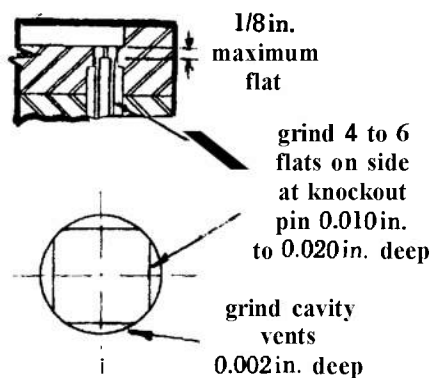
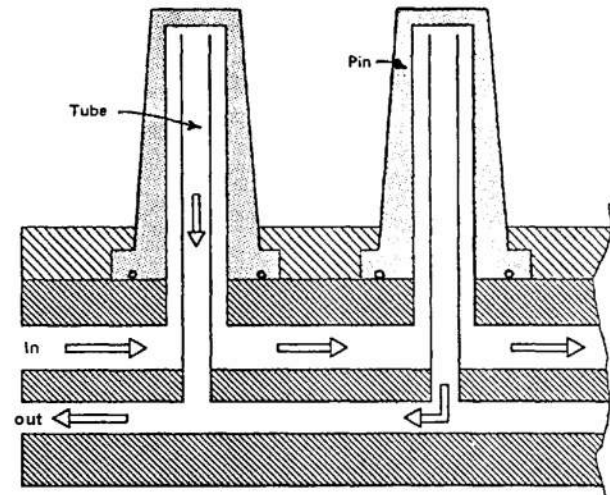


Figure 7-19. Self-cleaning Vents⁴



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Figure 7-20. Parallel Cooling of Pins, Correct Design (Robinson Plastics Corp.)²

through the mold plates. A cooling medium, usually water, is circulated continuously in and out of the mold plates spaced approximately 1.5-2 in. on center and 3/8-5/8 in. below the surfaces of both mold halves.

When a number of cooling channels are drilled parallel, they should be connected in parallel from the water supply and not in series. The outlets should be designed at least as large as the inlets.

Cores, cavities, and pins—depending on design—are cooled with bubblers. Bubblers usually are used when the core or pin is 0.5 in. or larger in diameter, and the height is more than two times the diameter. An appropriate design is shown in Fig. 7-20. In constructing a bubbler, two holes are drilled in the plate, one under the other. The metal between them is tapped and a noncorrosive bubbler pipe is screwed in. The “in” water channel must be directed so the bubbler pipe fills up with water before it overflows into the “out” channel. Again, the pipes should be designed in parallel and not a series.

Another core cooling design is shown in Fig. 7-21. The core is hollowed out and a spiral grooved stainless steel insert of the same taper as the core is emplaced. The water enters the bottom, travels up the spiral, and drops down a hole drilled in the center of the “out” channel. Although more expensive, this design offers superior temperature control over the conventional bubbler.

Large-core molds require water channels at various levels spaced about 1.5 in. on center. It is wise to provide the maximum amount of cooling possible when designing a mold, even if this additional cooling is not fully used.

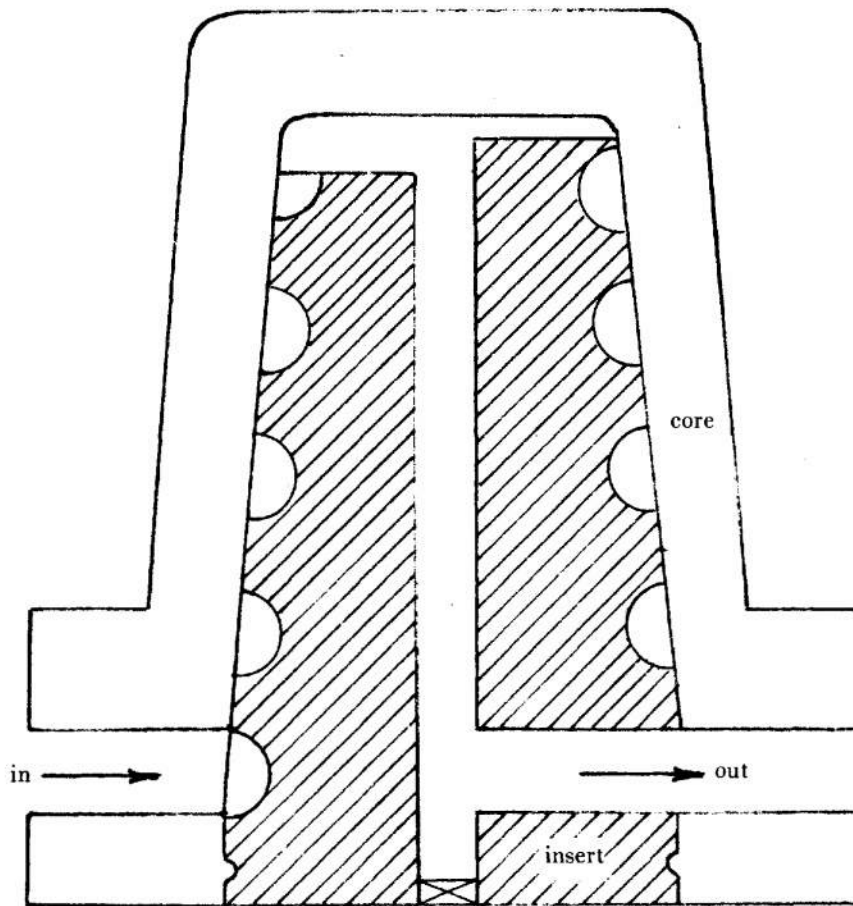
7-2.3 PARTING LINES

The parting line is the line formed on the part when the mold opens and closes, i.e., where the two halves of the mold meet. A part might have several parting lines if it has cam or side mechanisms. The design of the parting line depends upon the part geometry, tapers, tolerances required, ejection method, type of mold, esthetic requirements, inserts, venting, wall thickness, number of cavities, and location and type of gating as well as machine capabilities. Parting lines range

from a simple line on a flat plane to arcs of circles, which can be mechanically trimmed, to completely irregular lines which are difficult to make and maintain. Some factors to be considered in designing parting lines are:

1. It is always more difficult to maintain a dimension that crosses the parting line because of possible movement in the clamping mechanisms. Parts with close tolerances should be contained in the cavity.

2. The parting line is determined by the machine clamping capacity and daylight area. There must be sufficient clamping capacity per square inch of projected area parallel to the platens to prevent the mold from opening. In addition, there must be enough daylight area to permit part ejection. Deep cavity parts may require side cam mechanisms.



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Figure 7-21. Core With Insert to Provide Maximum Cooling²

3. The parting line also determines gate location. Gate location directly influences mechanical properties and esthetics.

7-2.4 TYPES OF MOLDS

There are two types of molds, namely, two-plate molds and three-plate molds. The terms "two" and "three" designate mold functions and are not related to the actual number of mold plates.

7-2.4.1 Two-Plate Molds

Two-plate molds are the least complex and expensive mold designs. In these molds the part and runner are ejected from the same opening. They can be of a single or multicavity design. The single cavity mold can be centergated by direct gating through the sprue bushing. However, in centergating, the sprue must be removed manually. Multicavity molds are either edge or subgated. Two-plate molds may require manual removal of the parts and runner or it may be automatically ejected and self-degating—i.e., automatic separation of part and runner. A two-plate mold is illustrated in Fig. 7-1.

7-2.4.2 Three-Plate Mold

A three-plate mold differs from a two-plate mold in that the sprue and/or runner are ejected from one plate opening and the part from a different opening (see Fig. 7-22). All three-plate molds are self-degating. The actual number of plates are three or more. These molds usually are centergated or have symmetrically located multi-gates. This offers the advantage of uniform fill and controlled shrinkages.

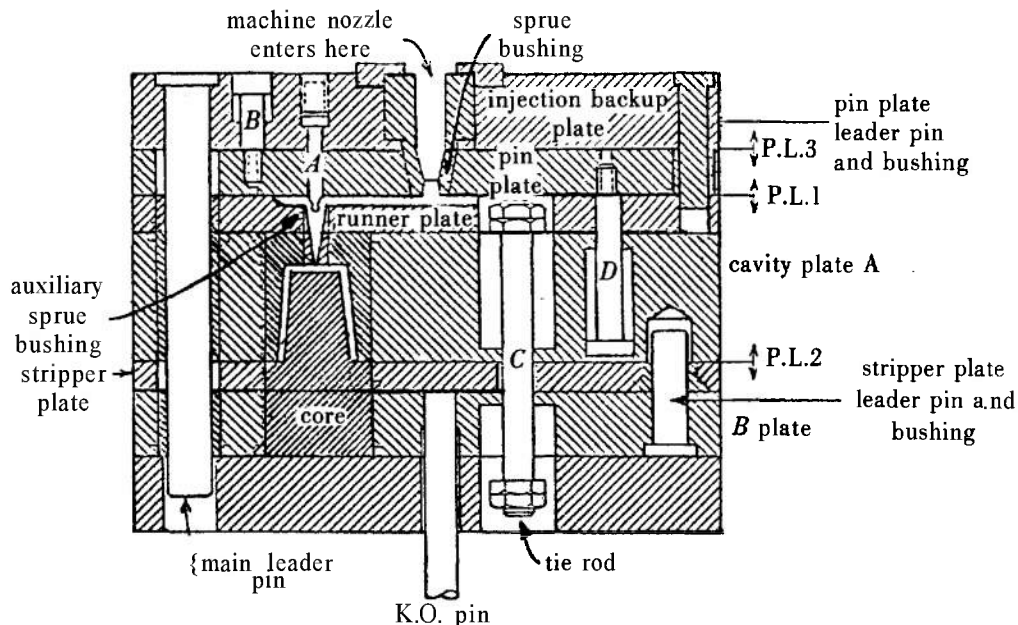
7-3 ROTATIONAL MOLDS

For a thorough discussion of rotational molds refer to Engineering Design Handbook, AMCP 706-312 *Rotational Molding of Plastic Powders*.

7-4 STAMPING MOLDS

7-4.1 MOLD MATERIALS

Aluminum or Kirksite can be used to construct prototype molds. However, molds from these materials will never produce close tolerance parts with finished edges since telescoping edges cannot be produced in these soft metals. Flash-free



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Figure 7-22. Schematic Drawing of a Three-Plate Mold in Closed Position²

parts cannot be produced using hardened steel edge inserts because the steel edges deform the aluminum and Kirksite. This destroys the close tolerances required for flash-free parts. Mold detail can be maintained fairly accurately in aluminum or Kirksite. For example after 400 "hits", a 0.008 in. radius (the sharpest edge to which aluminum can be designed) will have a 0.009-0.010 in. radius".

Grained patterns will "wash out" of aluminum or Kirksite after about 50-75 parts and are not recommended¹¹.

An inexpensive, satisfactory prototype mold can be made by casting aluminum to an under-sized shape and finishing the casting with aluminum powder filled epoxy or polyester. This type mold will produce accurate prototype parts and can easily accommodate design changes. The parts, however, will not be flash-free.

In production molds, if the telescoping edges are part of the cavity and/or plug, tool steels must be selected which permit hardening these edges. A Rockwell hardness of C60 or higher is recommended for the telescoping steel edges to prevent galling, spalling, etc. The hardness of the cavity and plug can be chosen as a function of the production volume. A Rockwell hardness of C40-45 is sufficient to prevent damage to the mold cavity and plug.

7-4.2 SURFACE FINISH

As with all molds, the surface finish of the cavity and plug depend upon the part design. Stamping G RTP will reproduce the mold finish with high fidelity. Grained patterns must have a hard chromium-flash finish not exceeding 0.001 in. In fact, a chromium-flash surface is preferred on all mold surfaces regardless of finish to prevent rusting and contamination.

Mold surfaces for exposed part surfaces must be free of any waviness. A vapor-blasted finish (yielding a 200-microinch surface) is preferred over highly polished surfaces for painted parts. Also, the rougher the die finish, the easier air can be vented and the part removed. The vertical mold surfaces must be line-polished when steep-walled, deep cylindrical parts are to be stripped from cylindrical cavities and plugs¹¹.

7-4.3 PART THICKNESSES

Plug and cavity surfaces should be as close as

possible to the theoretically exact shape of the part to be made. For example, the plug and cavity surface should not vary more than ± 0.003 in. from the nominal part thickness for small parts or ± 0.005 in. for parts over 3 ft² for Adzel G RTP material. This means that if the plug surface at a given point is 0 (zero), then the cavity at that point could vary as much as ± 0.003 in. of part thickness (or ± 0.005 in. for large parts). If the plug has a "high spot" of 0.002 in., then the cavity can have a low spot not to exceed 0.001 in. or a high spot of not more than 0.005 in. to stay within permissible tolerance¹¹.

7-4.4 MOLDED-IN HOLES

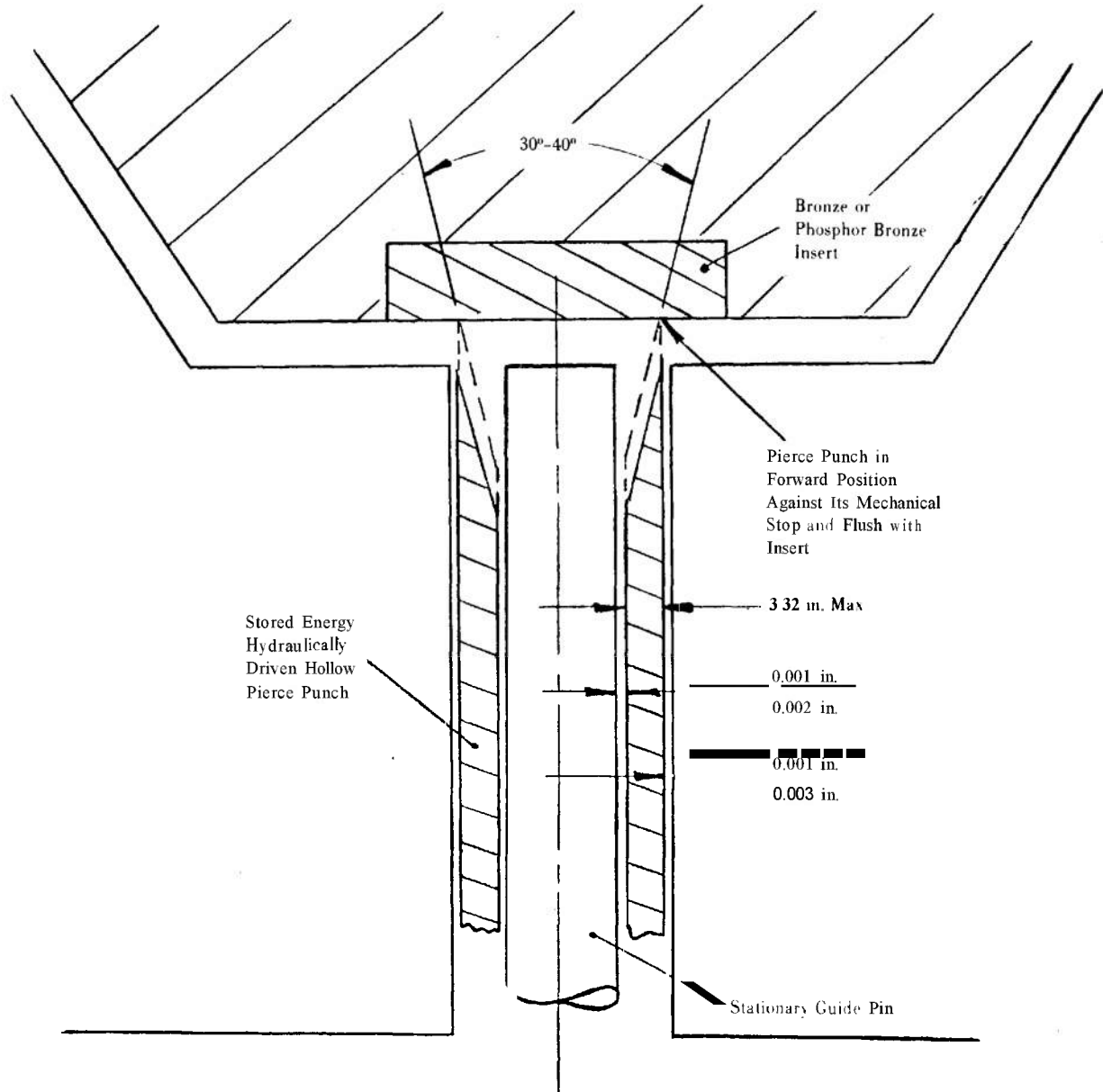
Flash-free, molded holes can be produced during stamping. When the hole is vertical or parallel with the press ram motion, fixed pierce punches are used. The punches must be located on the side from which the part is to be stripped. As a rule, the part will bind on the protruding punches, eliminating the need for additional undercuts. The part will nearly always stay on the mold half with the punches.

The pierce punches must incorporate the following design features":

1. Be polished.
2. Engage 1/16 in. maximum into the punch button, i.e., the pin is 1/16 in. longer than part thickness.
3. Be square ended.
4. Always be designed on the same side to which the molded part is to be held. In other words, ejector pins and pierce punch pins must be on the same side of the mold.
5. Be designed with 0.001 in. total clearance with hole-in-mold button. The holes for the mold button and pierce punches must be line-bored to obtain the close tolerances needed.

A hydraulically driven hollow pierce punch can be used to mold a hole on a sidewall. The following design parameters are recommended (see Fig. 7-23)¹¹:

1. The hollow pierce punch should have a wall thickness not exceeding 3/32 in. and be made from S-7 steel.
2. The hollow pierce punch should be guided internally by a guide pin with a 0.001-0.003-in. clearance.
3. The guide pin should be flush with the cavity wall.
4. The edges of the wall of the hollow pierce



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Figure 7-23. Hollow Pierce Punch, Side View"

punch should be tapered about a 60 deg angle.

5. The hydraulic cylinder should be operated via a stored energy system. It is imperative that the pierce punch is moved with force during all of its travel. Even the momentary delay of the hydraulic pressure buildup, such as that experienced when connecting the hydraulic cylinder directly to a hydraulic pump (without a stored

energy device), will render the design useless. The hollow pierce punch, regardless of pressure, will freeze when trying to form the slug.

6. The hollow pierce punch should start moving within about 2-5 deg before the press reaches bdc. A longer delay will prevent formation of molded walls of the hole.

7. The motion of the pierce punch should be

snappy. Since the total travel is generally only 0.100 in. (wall thickness), the speed should be such that the eye cannot quite follow the motion.

8. The hollow pierce punch should remain in its most forward position for at least 5 s. This time is needed to cool the slug/hole walls sufficiently to prevent resin flow and subsequent welding.

When the cost of hollow-pierce additions to the mold cannot be justified, the use of molded-in knockouts or drill guides for circular saw removal or drilling can be used. These practices will leave a "raw" edge of uncoated glass fibers which, if the hole is not subjected to exposure to water or solvents, is not harmful.

7-4.5 TELESCOPING EDGES

The mold must be equipped with close fitting hardened steel telescoping edges to produce flash-free parts. The telescoping edges must be properly designed to prevent deformation, chipping, and wearing. A satisfactory design used to stamp Adzel GRTP is shown in Fig. 7-24.

The infeed taper should not be steeper than 5 deg. Also, all surfaces of the telescoping edges should be polished or at least finished to a maximum 16-microinch roughness. Close clearances of the land are required to form flash-free parts. Some recommended tolerances are¹¹:

<u>GRTP Material</u>	<u>Tolerance, in.</u>
STX 100—Nylon 6	0.002-0.003
Adzel P-100-Polypropylene	0.001-0.002

Unlike most thermosets, flash on GRTP parts is not easily removed by tumbling and requires secondary hand operations. Therefore, it is recommended that finished part edges be produced in the die.

Although little or no lubrication of hardened telescoping edges is needed in production, it is advisable to break in a die using a generous coating of lubricant on these edges until they have had a chance to seat each other. The lubricant need not come in contact with the GRTP during forming if care is taken not to touch the lubricant during discharge¹¹.

7-4.6 HEEL BOXES

Special heel boxes must be designed into the mold set to guide the plug into the cavity under

load in order to prevent the shear edges from touching or taking up any side loads. Even though a properly designed telescoping edge forms a large heel box by itself, its lifetime is drastically reduced when it is called upon to contain side forces and work as an aligning mechanism in addition to its task of sealing the hot GRTP. Also, the telescoping edge would never align the mold cavity with the plug when large, inclined, asymmetrical parts are to be formed.

7-4.7 STOP BLOCKS

GRTP cannot be stamped in molds sitting on stop blocks. Stop blocks must be designed for safety purposes only, i.e., to prevent the empty mold surfaces from cracking into each other. Therefore, stop blocks, pin retractors, keys, heelblocks, spacers, etc., must permit the empty mold to close within 0.020 in.

7-4.8 VENTING

Air may be entrapped during stamping and cause localized burning and surface defects. Therefore, molds should be vented. Deep ribs or box-like forms can be vented by use of sintered metal plugs. The plastic will not seep into the fine top disc but yet the air will vent out the bottom.

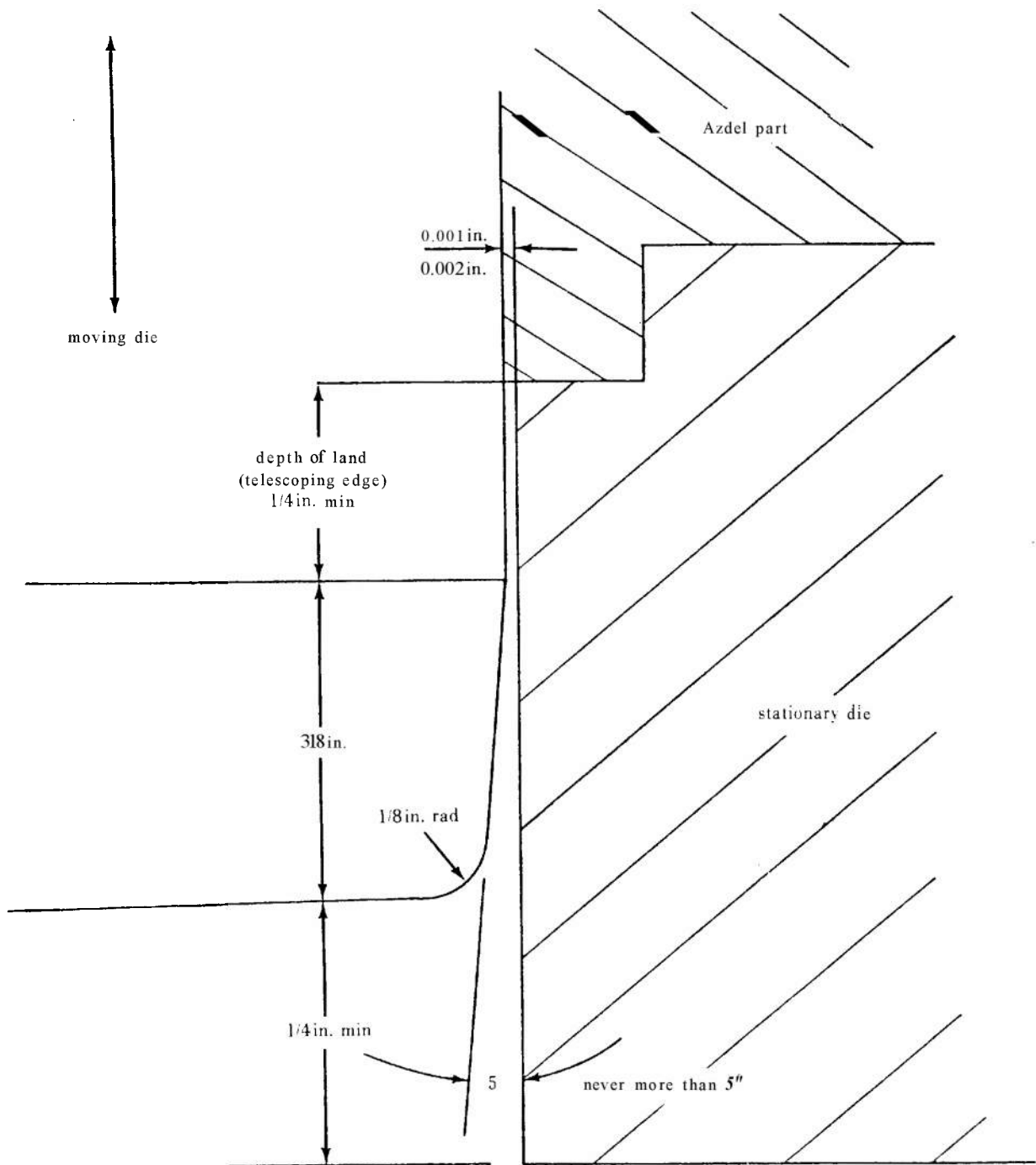
7-4.9 TEMPERATURE CONTROL

7-4.9.1 Heating

Heated dies are required when stamping some GRTP materials to obtain satisfactory surface properties and dimensional stability. For example, STX nylon 6 sheeting requires molds of 100°-150°C (212°-300°F) (Ref. 12). Die heating usually is accomplished by means of circulating fluid or electric heaters.

7-4.9.2 Cooling

Water circulating cooling channels are used when cool molds are required for stamping GRTP materials. Cooling channels 0.25-0.5 in. in diameter about 2 in. apart and 1-1.5 in. from the mold surface have been used successfully. The smallest diameter cooling holes with the closest spacing give the best cooling. A simple back-and-forth pattern of straight through holes is usually sufficient. Both the plug and cavity must be cooled but



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Figure 7-24. Design of Telescoping Edges"

there should be proportionately more cooling channels in the plug than in the cavity.

Cooling channels should be in parallel to the waterline and never in series. Each cooling outlet should be equipped with a valve to regulate the rate of flow independently. Plant cooling water is generally sufficient to keep the mold at about 15°-21°C (60°-70°F) but a cooler with a closed loop recirculation system can be used.

7-4.10 DRAFT

The minimum draft required to remove a part depends upon part configuration, depth of draw, part size, and type of GRTP used. Parts having 1-7/16 in. high walls with only 1.5 deg draft have been stripped. For deeper parts, 3 deg draft is probably the minimum. Since the greater the draft the easier the part is formed and stripped, the largest permissible draft angle should be chosen.

7-4.11 EJECTION SYSTEMS

Part ejection is accomplished with ejecting devices similar to injection molding ejector pins. Care should be taken to assure that the part stays in the mold half which has the ejector pins. It is important that the ejector pin be flush with the mold to prevent an increase in the cooling cycle and/or formation of sinkmarks.

GRTP will shrink onto the plug and away from the cavity. Therefore, it is far easier to incorporate very small undercuts on the plug to pull the part out of the cavity and strip it from the plug than the other way around. Of course, there will be exceptions where this cannot be done.

Location, number, and size of stripping pins, plates, or rings must be sufficient to prevent cocking and/or distortion of the part. The larger the stripper pin diameter, the better. All stripping devices will leave marks on the part. They must be located on the back side of the part or hidden by camouflaging into the design. Clearances between the stripper pin and stripper pin guide hole should be +0.001 in. around the perimeter of the pin. If this clearance is substantially larger, the GRTP will flow inbetween pin and hole, and will jam the pin.

If a stripper plate is used to operate several pins simultaneously, it must be hard enough to prevent cold flow. During molding, the area of the stripper pin can reach pressures of 2500 psi. The

pin foot must therefore be of sufficient size, and the plate of sufficient hardness, to prevent coining. When stripper plates are operated pneumatically or hydraulically, provisions must be made to prevent cocking. Large size guides and guide bushings, rack and pinion or hydraulic-lock arrangements must be provided to assure the cylinders are and remain synchronized.

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CHAPTER 8

GLASS-REINFORCED THERMOPLASTICS (GRTP) APPLICATIONS

The applications and economics associated with the use of GRTP parts are presented.

8-1 APPLICATIONS

Glass-reinforced thermoplastics (GRTP) are moving into a growing number of applications in this and other countries. The intent of this chapter is to acquaint the reader and design engineer with some of the commodities in which the present GRTP are used.

There are several prominent reasons behind the trend to GRTP, namely:

1. The improved performance of the newer resin-glass systems such as better resistance to corrosion from hot water and detergents, superior dimensional stability, internal lubrication, and higher temperature performance.

2. Cost reductions as a result of the ability to injection mold one-piece finished functional items. This eliminates the costly assembly and finishing techniques required with multipart metal components.

3. The design flexibility of thermoplastics permits more complex design concepts not previously possible with metals because of the limited production techniques.

4. The wide range of GRTP enables the design engineer to select a material to meet specific property requirements.

5. Electrical insulation is inherent in the material.

6. Design flexibility permits a wide variety of assembly techniques for maximum strength.

7. The light weight permits cost savings in processing, handling, shipping, storage, etc.

8. The material entails reasonable production tooling costs.

Table 8-1 lists typical GRTP applications in some of the more prominent market areas. A general breakdown of the GRTP market has been broadly categorized as: transportation — 62%, appliance/electronic/equipment — 33%, and consumer items — 5% (Ref. 1).

The GRTP usage for 1973 has been estimated at 130 million pounds broken down as follows:

1. Polypropylene — 40 million pounds
2. Nylon — 23 million pounds

3. Styrenics (Polystyrene, ABS, SAN) — 20 million pounds

4. Polyethylene — 13 million pounds

5. Other Engineering Polymers — 34 million pounds.

Within the group "Other Engineering Polymers" — e.g., polycarbonate, acetal, thermoplastic polyester — thermoplastic polyester is the largest and fastest growing material.

Based on the expanding GRTP applications and new glass-reinforced thermoplastic systems being developed, future growth is projected at 27% compounded annually over the next five years. This will result in a 1978 usage of approximately 429 million pounds.

Table 8-2 illustrates the growth of GRTP in the automotive industry over three years. It also exemplifies the breadth of materials used in a single industry.

8-2 ECONOMICS

Some of the current GRTP applications having been reviewed, the next step in putting this market in perspective is to compare the cost/performance characteristics with competing materials. The materials chosen for comparison should have a number of qualities in common. They should be those used where low to moderate strength is required; can be molded or cast to close tolerances; permit considerable design freedom; and use high production processes. GRTP are usually compared with cast brass, cast iron, and die cast aluminum or zinc. Unfortunately, due to the volatility in prices as of this writing, no attempt will be made to compare actual cost data. However, a realistic and useful materials comparison must incorporate material cost, material performance, and processing — discussed in the paragraphs that follow.

8-2.1 MATERIAL COSTS

For a GRTP system this should include the selected resin, additives (pigments, lubricants,

TABLE 8-1. GRTP ITEMS

Item	Glass-Reinforced Thermoplastics	Item	Glass-Reinforced Thermoplastics
<u>Automotive Industry</u>		<u>Electrical-Electronic Industry</u>	
Automotive rear end panel	Polyester	Fluorescent light fixture	Nylon
Valve stem oil seats	Nylon	Electric connectors	Polyester
Carburetor spacer plates	Nylon	Coil bobbins	Polyester
Ignition coil bobbins	Polyester	Motor brush holders	Polyester
Transmission thrust washers	Nylon	Timer parts	Polyester
Breaker plate control arm	Nylon	Coaxial switch mounting panel	SAN
Camper tops	Polyethylene, ABS, ASA	Speed sensing switches on electric motors	Nylon
Camper holding tank	HDPE	Gears for timer	Nylon
Car top carriers	HDPE	Electrical fuel pump housing	Acetal
Battery cases	Polypropylene		
Battery clamp	Polyester	<u>Recreational</u>	
Trailer brake housing	Nylon	Little League Baseball bat	Nylon
Instrument panels	ABS, SAN, Polystyrene	Canoe	HDPE
Window louvers	Polyester	Paddle tennis racquet	Nylon
Lamp housings	Polypropylene, Polyester	Motion picture projector housing	Polystyrene
Fender liners	Polypropylene	Microphone stand	ABS
Windshield washer tank	Polypropylene	Tape recorder housing	Polystyrene
Gas caps	Polyester	Fishing rod	SAN
Fuel pumps	Polyester		
Fuel vapor separators	Polyester	<u>Miscellaneous</u>	
Distributor cap	Polyester	Pallets	HDPE
Gear shift consoles	SAN	Luggage	HDPE
Torque-converter cover	Polypropylene	Bus and aircraft luggage racks	HDPE
Quarter window latch	Nylon	Pruning shears handle	Nylon
Alternator rectifier assy.	Polysulfone	Wristwatch back plate	Nylon
Air cleaner tray	Polypropylene	Mop head	Polypropylene
Radiator fan shroud	Polypropylene	Water softener valve	Polyester
Air vent control housing	Nylon	Pharmaceutical beaker	Polyester
Fan shrouds	Polypropylene	Gears (AGMA quality Nos. 6-10)	Polyester, Nylon, Acetal
Lamp housing	Polypropylene	Bearings	Polyester, Nylon, Acetal
Steering gear sector	Nylon	Safety razor	Nylon
Windshield washer motor	Nylon	Transport manifold for office copying machine	Polycarbonate
Handle turn signal	Polystyrene	Handle, REDEYE missile launcher	Polycarbonate
<u>Construction</u>			
Block and tackle	ABS		
Septic tanks	HDPE		
Tie rods for concrete form	Nylon		
<u>Appliances</u>			
Electric drill handle	Nylon		
Water meter housing	Polycarbonate		
Centrifugal pump	Polypropylene		
Electric knife handle	Polyester		
Humidifiers, air conditioner housings	Polyester		
Xerox office machine housing	Polycarbonate		
Valve automatic washer	SAN		

**TABLE 8-2. FIBERGLASS REINFORCED
THERMOPLASTICS AUTOMOTIVE APPLICATIONS
BY MODEL YEAR¹**
(Million pounds of molded parts)

	1972	1973	1974
ABS	2.635	4.720	10.172
Acetal	0.170	0.192	0.202
Nylon	1.780	3.992	5.407
Polycarbonate		0.544	0.544
Polyester (Thermoplastic)		0.350	4.927
Polyethylene	5.400		
Polyphenylene Oxide (Modified)		0.020	0.023
Polypropylene	9.725	26.392	26.232
Polystyrene	5.024	6.293	6.377
Polysulfone			
SAN	11.357	10.952	12.984
TOTAL	36.1	53.5	66.9

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flame retardants, etc.), and glass as well as the materials compounding cost. The two main compounding techniques are:

1. Blending a reinforced pellet concentrate with unreinforced pellets to obtain the desired glass concentration

2. Blending powder and glass in a mixer and direct molding the blend.

The pellet concentrates offer ease of handling, less storage space, higher weight truckloads, and an overall neater process; the powder technique offers less glass degradation, slightly higher properties, and lower expenses. There is a place for both techniques in the market. However, as volume increases, material economics will become predominantly more important in deciding which process to employ.

Other things being equal, normally, at the same glass concentration the direct molding of powder blended with glass is less expensive than molding glass-reinforced pellet concentrate with unreinforced pellets. This is because the pellet concen-

trate entails the expense of a compounding-extrusion step.

8-2.2 MATERIAL PERFORMANCE

In ranking material performance in economic order of merit, the property data concerned are usually divided by the cost per unit volume of material over a range of temperatures. The adverse effects of temperature and moisture are important factors in the economic performance ranking of GRTP as well as their superior lubricity, corrosion, and chemical resistance.

The lighter weight of GRTP influences costs. Light weight permits lower shipping and handling costs, and reduces assembly and installation cost—especially on larger components.

8-2.3 PROCESSING

Processing—molding, die casting, machining, and finishing—costs for any material can vary, depending on part size and production volume. The variation for smaller parts can be minimized by using multiple-cavity molds. Processing costs are also influenced by part thickness. This factor can be severe with GRTP. In die cast metals, it would be much less significant because of their greater thermal conductivity. Finishing costs—such as machining, trimming, painting, plating, decorating, bonding, and joining—are very important and must be considered in each material comparison.

The greater versatility of GRTP processability can also influence costs through design economies.

REFERENCE

1. James R. Best and Thomas C. Kelly, "The Growth of the Fiber Glass Reinforced Thermoplastics Market in the United States", *29th Annual Technical Conference, Reinforced Plastics/Composite Institute, The Society of the Plastics Industry, Inc.*, Washington, DC, 1974.

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APPENDIX A

TRADE NAMES OF GRTP MATERIALS

Trade Name	Material	Supplier
Celcon CR20	Acetal Copolymer	Celanese Plastics Co.
Celcon GC25	Acetal Copolymer	Celanese Plastics Co.
Celcon M90	Acetal Copolymer	Celanese Plastics Co.
Formaldafil G80	Acetal Copolymer	Fiberfil Div., Dart Industries, Inc.
Formaldafil J80	Acetal Copolymer	Fiberfil Div., Dart Industries, Inc.
Thermocomp KFX	Acetal Copolymer	Liquid Nitrogen Processing Corp.
Thermofil G	Acetal Copolymer	Thermofil, Inc.
LNP Fulton 404	Acetal Copolymer	Liquid Nitrogen Processing Corp.
LNP K	Acetal Copolymer	Liquid Nitrogen Processing Corp.
LNP KFL	Acetal Copolymer	Liquid Nitrogen Processing Corp.
Thermocomp PDX-301	Acrylic	Liquid Nitrogen Processing Corp.
Absafil G & J Series	ABS	Fiberfil Div., Dart Industries, Inc.
Thermocomp AF	ABS	Liquid Nitrogen Processing Corp.
Thermofil D & DSE	ABS	Thermofil, Inc.
Fluon G 307	PTFE	ICI America, Inc.
Fluon VG 15F	PTFE	ICI America, Inc.
Fluon VG 25F	PTFE	ICI America, Inc.
LNP 803	CTFE	Liquid Nitrogen Processing Corp.
Plaskon 2100	CTFE	Allied Chemical
Tefzel	ETFE	Du Pont
Thermocomp UF	ETFE	Liquid Nitrogen Processing Corp.
Nylafil G 1 and 3 Series	Nylon 6	Fiberfil Div., Dart Industries, Inc.
Nylafil J 3 and 13 Series	Nylon 6	Fiberfil Div., Dart Industries, Inc.
Nylafil S Series	Nylon 6	Fiberfil Div., Dart Industries, Inc.
Nypel 6000 Series	Nylon 6	Nypel, Inc.
Plaskon 8000 Series	Nylon 6	Allied Chemical
STX	Nylon 6	Allied Chemical
Thermocomp PF, PFL	Nylon 6	Liquid Nitrogen Processing Corp.
Thermofil N0500, N1500, N3000	Nylon 6	Thermofil, Inc.
Nylafil	Nylon 6/6	Fiberfil Div., Dart Industries, Inc.
Nypel 6600 Series	Nylon 6/6	Nypel, Inc.
Thermocomp RF & RL Series	Nylon 6/6	Liquid Nitrogen Processing Corp.
Thermofil N3 Series	Nylon 6/6	Thermofil, Inc.
Zytel 70G Series	Nylon 6/6	Du Pont
Nylafil G & J I2 Series	Nylon 6/10	Fiberfil Div., Dart Industries, Inc.
Thermocomp QF Series	Nylon 6/10	Liquid Nitrogen Processing Corp.
Thermofil N5 Series	Nylon 6/10	Thermofil, Inc.
Nylafil G & J 4 Series	Nylon 6/12	Fiberfil Div., Dart Industries, Inc.
Thermocomp IF Series	Nylon 6/12	Liquid Nitrogen Processing Corp.
Zytel 77G Series	Nylon 6/12	Du Pont

APPENDIX A (cont'd)

Trade Name	Material	Supplier
Rilsan 2M	Nylon 11	Rilsan Corp.
Thermocomp HF Series	Nylon 11	Liquid Nitrogen Processing Corp.
Thermofil N9 Series	Nylon 12	Thermofil, Inc.
Vestamid L Series	Nylon 12	Chemische Werke Huls AG
Lexan	Polycarbonate	General Electric Co.
Polycarbafil G & J Series	Polycarbonate	Fiberfil Div., Dart Industries, Inc.
Thermocomp DF Series	Polycarbonate	Liquid Nitrogen Processing Corp.
Thermofil R Series	Polycarbonate	Thermofil, Inc.
Celanex	Polyester	Celanese Plastics
FR-PET	Polyester	Tiejin Ltd.
Tenite	Polyester	Eastman Chemical Co.
Thermocomp WF	Polyester	Liquid Nitrogen Processing Corp.
Thermofil E Series	Polyester	Thermofil, Inc.
Valox	Polyester	General Electric Co.
Versel	Polyester	Allied Chemical Co.
Thermocomp J & JF Series	Polyethersulfone	Liquid Nitrogen Processing Corp.
Alathon	Polyethylene	Du Pont
Ethofil	Polyethylene	Fiberfil Div., Dart Industries, Inc.
Thermocomp FF Series	Polyethylene	Liquid Nitrogen Processing Corp.
Thermofil F Series	Polyethylene	Thermofil, Inc.
Noryl	Mod. PPO	General Electric Co.
Thermocomp 2F Series	Mod. PPO	Liquid Nitrogen Processing Corp.
Thermofil L Series	Mod. PPO	Thermofil, Inc.
Ryton	Polyphenylene Sulfide	Phillips Petroleum Co.
Thermocomp OF	Polyphenylene Sulfide	Liquid Nitrogen Processing Corp.
Adzel 100	Polypropylene	G.R.T.L. Co.
Profax	Polypropylene	Hercules, Inc.
Profil	Polypropylene	Fiberfil Div., Dart Industries, Inc.
Propathene	Polypropylene	Imperial Chemical Industries Ltd.
Thermofil P Series	Polypropylene	Thermofil, Inc.
Thermocomp MF	Polypropylene	Liquid Nitrogen Processing Corp.
Styrofil	Polystyrene	Fiberfil Div., Dart Industries, Inc.
Thermocomp CF	Polystyrene	Liquid Nitrogen Processing Corp.
Thermofil A Series	Polystyrene	Thermofil, Inc.
Sulfil	Polysulfone	Fiberfil Div., Dart Industries, Inc.
Thermocomp TF Series	Polyurethane	Liquid Nitrogen Processing Corp.
Urafil	Polyurethane	Fiberfil Div., Dart Industries, Inc.
Thermocomp VF Series	PVC	Liquid Nitrogen Processing Corp.
Thermofil V Series	PVC	Thermofil, Inc.
Acrylafil	SAN	Fiberfil Div., Dart Industries, Inc.
Adzel A 201	SAN	G.R.T.L. Co.
Thermocomp BF	SAN	Liquid Nitrogen Processing Corp.
Thermofil B	SAN	Thermofil, Inc.

APPENDIX B

MATERIAL SPECIFICATIONS, STANDARDS, AND TEST METHODS

Sources of standards, specifications, and test methods, published by Government and non-Government agencies, which are applicable to GRTP's, are listed. A brief digest of the contents of the various publications is presented together with cost, schedule of issue, custodian of the publication, and where to obtain copies.

B-1 INTRODUCTION

The purpose of this appendix is to acquaint the reader with sources of specifications, standards, and test methods applicable to glass-filled thermoplastics. Standards are prepared and published by technical societies, trade associations, Government agencies, and military organizations. Such standardization provides industry with a basis for mass production; production of uniform goods; and economies in time and material through standard designs, equipment, procedures, and testing.

National technical and trade associations represent entire industries to bring consumer requirements into line with the current engineering and manufacturing practices. Some of these organizations are concerned with the preparation of standards while others develop test methods or certification to guarantee that the item meets a specified standard.

B-2 SPECIFICATIONS, STANDARDS, AND TEST METHODS INDEXES

Available indexes to specifications, standards, and test methods—both Government and non-Government—are described in the paragraphs that follow.

B-2.1 GOVERNMENT SOURCES

B-2.1.1 US Department of Commerce, National Bureau of Standards (NBS)

B-2.1.1.1 National Bureau of Standards' World Index of Plastics Standards

This computer-produced Index contains the printed titles of national and international standards on plastics and related materials. These standards are published by technical societies,

trade associations, Government agencies, and military organizations. The title of each standard can be found alphabetically under all the significant key words which it contains. The date of publication or last revision designating the standard-issuing organization appears as part of each entry. A total of 124 standardizing agencies are listed.

This document is available from the Superintendent of Documents, US Government Printing Office, Washington, DC 20402. Its order number is SD-C13.10:352 and the price is \$5.50.

B-2.1.1.2 Index of US Voluntary Engineering Standards

This computer-produced Index contains the permuted titles of voluntary engineering and related standards, specifications, test methods, and recommended practices published by some 360 US technical societies, professional organizations, and trade associations. It does not include Federal and Military, or company standards and specifications. This is a Key-Words-in-Context index. The title of each standard can be found alphabetically under all the significant key words which it contains. The date of publication or last revision, the standard number, and an acronym designating the standards-issuing organization appear as part of each entry.

When applicable, cross references to other organizations besides the group originally issuing the standard are provided. This is a general, rather than a specialized compilation, and documents of interest in plastics in this source would probably be listed in NBS's World Index of Plastics Standards.

This index is available from the Superintendent of Documents. Its order number is C13.10:329 and the price is \$9.90. It can also be obtained on microfiche from the National Technical Information Service, US Department of Commerce, Springfield, VA 22151 as COM 71-50172 at \$0.95.

B-2.1.1.3 List of Voluntary Product Standards, Commercial Standards, and Simplified Practice Recommendations

This brief, free NBS publication is intended to assist all interested parties in obtaining copies of Voluntary Product Standards, Commercial Standards, and Simplified Practice Recommendations published by the US Department of Commerce. It contains subject and numerical indexes of the standards available, and instructions for ordering them.

The Index of Standards provided in this pamphlet covers 89 subject areas. These standards involve end items to a considerable degree, rather than raw materials. Printed standards available from the Superintendent of Documents are shown in the Index with the actual cost in the price column.

If the symbol "M" appears in the price column, the standard is out of print.

B-2.1.1.3.1 Voluntary Product Standards

Voluntary Product Standards are standards developed under procedures established by the Department of Commerce. The standards may include dimensional requirements for standard sizes and types of various products; technical requirements; and methods of testing, grading, or marking. The objective of a Voluntary Product Standard is to establish requirements which are in accordance with the principal demands of the industry and, at the same time, are not contrary to the public interest.

Although the use of a Voluntary Product Standard is voluntary, when reference to it is made in contracts, labels, invoices, or advertising literature, the provisions of the standard are enforceable through use of legal channels as a part of the sales contract. Requests for single copies of these standards or inquiries regarding their status should be sent to the Office of Engineering Standards, NBS, Washington, DC 20234.

B-2.1.1.3.2 Existing Commercial Standards and Simplified Practice Recommendations

Documents identified by the abbreviations (CS) and (R) are being phased out and replaced by Voluntary Product Standards.

B-2.1.2 US Department of Defense (DOD)

B-2.1.2.1 Department of Defense Standardization Manual 4120.3-M

This manual, as changed by MIL-STD-961 and MIL-STD-962, was developed by and is maintained in cooperation with the Departments of the Army, Navy, and Air Force and the Defense Supply Agency in accordance with Department of Defense Directive 4120.3. It is mandatory for use by all defense activities. It sets forth the scope, purpose, and basic objectives of the Defense Standardization Program and provides a statement of the principles under which this program is to be carried out. The manual includes detailed instructions for preparation of standardizing documents—including specifications, standards, and handbooks—both Federal and Military.

Copies are available at \$2.50 from the Superintendent of Documents.

B-2.1.2.2 Department of Defense Index of Specifications and Standards (DODISS)

The DODISS lists the unclassified Federal, Military and Departmental specifications, standards and related standardization documents, and those Industry documents which have been adopted by the Department of Defense.

The DODISS is comprised of: Part I—Alphabetical Listing, Part II—Numerical Listing, and Part II Appendix—A cumulative listing of cancelled documents. This latter appendix, published on a triennial basis, is kept current by adding to it cumulative cancellation listings of the DODISS Part II Supplement and subsequent cancelled listings appearing in the Basic DODISS PART II. This Part II Appendix is not automatically distributed. Military activities desiring copies can obtain them by submitting DD Form 1425 to:

Commanding Officer
Naval Publications and Forms Center
5801 Tabor Ave.
Philadelphia, PA 19120.

Private industry and individuals may purchase the Part II Appendix from the Superintendent of Documents for \$2.00.

The DODISS Index covers all subjects, not just plastics. It does not provide an alphabetical breakdown of all key words used in the specification titles. The alphabetization is based solely on

the first significant word in the title. The letter after MIL- refers to the first letter of the first word of the title.

In the DODISS listing, "L" indicates a limited coordination document and "Q" indicates that a Qualified Products List (list of manufacturers' products tested and known to meet the requirements of the specifications) has been issued. The Military Specifications are those beginning with MIL and the Federal Specifications are those with letter combinations, such as L-P-383, ZZ-R-001415, etc. The FSC number listed is the Federal Supply Classification Code listing. "PREP" is the code for the preparing agency, and those designations under "CUSTODIAN" represent the Army, Navy, and Air Force. These agencies are responsible for coordinating the documents. Letters such as "A", "B", etc., after the specifications refer to revisions; the original document does not carry a letter designation. Numbers in parentheses after specifications are changes—usually minor revisions, additions, or deletions.

The DODISS can also be used by searching the numerical listing in Part II, Section A. Section A includes the additions and changes to standardization documents listed in Section B.

Part II, Section B, is a ready-reference listing of additions, changes, and cancellations to standardization documents since the previous bi-monthly supplement. This list is issued with supplements effective 1 September, 1 November, 1 January, and 1 May. The supplements include changes in entries and cancellations.

Part II, Section A, contains an annual compilation of documents cancelled during the previous year. The cumulative collection of cancelled documents is now published on a triennial basis as an Appendix to the Part II basic document.

The organization of the Numerical Listing (Part II) is as follows:

- Military Specifications
- Military Standards
- Federal Specifications
- Federal Standards
- Qualified Products List
- Industry Documents
- International Standardization Documents
- Military Handbooks
- Federal Handbooks
- Air Force-Navy Aeronautical Standards
- Air Force-Navy Aeronautical Design Standards

- Air Force-Navy Aeronautical Specifications
- US Air Force Specifications
- Other Departmental Documents
- Air Force-Navy Aeronautical Bulletins
- US Air Force Specifications Bulletins.

The use of the DODISS is mandatory on all military activities. This means that the Federal and Military specifications, standards, and related standardization documents must be considered in identifying items for procurement actions.

The DODISS index and supplements may be purchased at \$20.00 from the Superintendent of Documents.

B-2.1.2.2.1 Military Handbooks

These handbooks generally are guides to a subject area and are often concerned with covering the salient properties and intended uses of current Federal and Military specifications. Military activities desiring copies can obtain them by submitting DD Form 1425 to the Naval Publications and Forms Center. Others may obtain copies by sending a check for the purchase price to the Superintendent of Documents.

B-2.1.2.2.2 Military Standards

Military Standards are issued in two forms: MIL-STD-XXXX, which are general in nature and presented in book format; and those listed as MS-XXXX, which are specific to end items or parts and are presented in sheet format. The book format standards are comprehensive presentations of engineering practices (including test methods), procedures, processes, codes, safety requirements, symbols, abbreviations, nomenclature, type designations, and characteristics for standard equipments, either singly or in families. Military Standards in the book format are also used to cover overall characteristics of a family of end items or major components. They are listed in Part II of the DODISS.

Military Standards are either Coordinated Standards or Limited Coordination Standards—the Limited Coordination Standards have the letter "L" preceding the MIL-STD or MS number designation; the Coordinated Standards are unmarked. The Coordinated Standards are concurred in by all interested activities; the Limited Coordination Standards are issued by one department to satisfy an immediate need.

Military Standard revisions are indicated by

the addition of a capital letter following the designation number, and revised pages by the date of the Change Notice.

B-2.1.2.2.3 Military Specifications

These specifications are developed and administered by the Department of Defense, and each is assigned to a custodian from the appropriate department.

The designations in the lower left-hand corner of the last page list the custodians, review activities, and the user activities for the Army, Navy, and Air Force. These are given in code form, the code being given in the front of the DODISS Part II.

Military Specifications are designated by an identification system consisting of three parts. The first part, MIL, is an abbreviation for military. The second part is a single letter which is the first letter of the title of the specification. The third part is the serial number followed by a letter indicating revisions if appropriate. The numbers in parentheses represent amendments.

When a specification has had limited coordination, an "L" appears in the index entry before the document number and a parenthetical suffix code designating the sole coordinating agency after the number on the specification document.

B-2.1.2.2.4 Qualified Products Lists

Some Military Specifications have Qualified Products Lists (QPL). As a means of expediting contract awards and deliveries of certain products, manufacturers sometimes are required to have their products pretested, either by a Government or a designated independent laboratory, to determine whether the products meet the specific requirements of Government specifications. If the products comply, the manufacturer's product may be placed on a Qualified Products List. These QPL's, which may be either Federal or Military, are prepared for only those specifications which require prequalification tests.

B-2.1.2.3 Naval Ordnance Systems Command, "Index of Ordnance Specifications and Weapons Specifications"

The Naval Ordnance Systems Command, Washington, DC, prepares this document and supplement. This publication—containing five parts—

provides a list of NAVORD OS (Ordnance Specifications) and WS (Weapons Specifications) specifications, descriptions and requirements, covering materials, articles, devices, explosives, parts or assemblies, and processes used by the Naval Ordnance Systems Command. A description of the parts follows:

1. Part 1 is a numerical listing of NAVORD OS numbers issued, including security classification, document number, latest revision, title, and Federal Supply Class (FSC) number when known.

2. Part 2 is a listing of NAVORD WS numbers and is otherwise similar to Part 1.

3. Part 3 is an alphabetical listing of active documents listed in Parts 1 and 2.

4. Part 4 is a numerical listing of cancelled OS documents.

5. Part 5 is a similar listing of cancelled WS documents.

The index and specifications may be obtained from the Commanding Officer, Naval Ordnance Station, Central Technical Documents Office, Louisville, KY 40214, Attn: Code 80121.

B-2.1.2.4 Department of Defense Single Stock Point for Specifications and Standards

This brochure is a brief outline of the Specifications and Standards Program, and is offered to private industry as an aid to facilitate the obtaining of specifications and standards required to do contractual business with the Department of Defense. Index subjects are:

1. DOD-SSP (Single Stock Point) Highlights
2. How to Order Specifications and Standards
3. Subscription Service (Automatic Distribution)
4. Redistribution of Specifications
5. DODISS (Department of Defense Index of Specifications and Standards)
6. Inquiries and Complaints.

The Naval Publications and Forms Center (NPFC), 5801 Tabor Avenue, Philadelphia, PA 19120, is the Department of Defense Single Stock Point (DOD-SSP) for unclassified specifications and standards throughout the Department of Defense for military procurement. It has the responsibility of indexing, determining requirements, procuring, receiving, distributing, issuing, and controlling those current specifications and standards listed in the DODISS. The following types of documents are stocked and distributed:

Military Specifications

Military Standards
 Federal Specifications
 Federal Standards
 Qualified Products Lists
 Industry Documents
 Military Handbooks
 Air Force-Navy Aeronautical Standards
 Air Force-Navy Aeronautical Design Standards
 Air Force-Navy Aeronautical Specifications
 US Air Force Specifications
 Other Departmental Documents
 Air Force-Navy Aeronautical Bulletins
 US Air Force Specifications Bulletins.

Customers of the DOD-SSP include all military services; Federal, state, and municipal agencies; foreign governments; and industrial and commercial firms, both national and foreign. Specifications and standards are issued to private industry on an "as ordered basis" without charge.

Requests for copies of specifications and standards can be obtained from the Naval Publications and Forms Center preferably by order form, DD Form 1425, or telephone request at (215)697-3321.

B-2.1.2.5 Plastics Technical Evaluation Center (PLASTEC)

This Center, which is the Department of Defense (DOD) information analysis center with responsibility in plastics, has issued documents that involve standardization, described in pars. B-2.1.2.5.1 and B-2.1.2.5.2. Copies may be purchased from the National Technical Information Service by AD Numbers 771 008, \$4.00; and 662 049, \$6.00, respectively.

B-2.1.2.5.1 Government Specifications and Standards for Plastics, Covering Defense Engineering Materials and Applications (Revised) Note 6C

This document lists the specifications and standards for those plastic materials and plastics applications which are considered to be of interest to engineers concerned with the design, development, production, and handling of defense hardware. Included are specifications for the basic or raw materials, composite materials, and the items and applications of potential defense concern. Excluded are specifications on life-situation items: clothing, utensils, and furniture, and decorative or preservative coatings.

The body of the material is presented in five parts:

1. Specifications for or involving specific plastic materials, title-stated or otherwise identified
2. General reference documents
3. Specifications for or involving unspecified plastics
4. Subject index
5. Numerical index.

Complete citations are given, covering: number, date, title, the existence of a QPL, the status of coordination among the services (whether limited or not), the agency which prepared the specification, and the custodian of the specification.

B-2.1.2.5.2 Guide to Test Methods for Plastics and Related Materials

This document lists test methods pertaining to plastic materials and processes. The methods listed are identified from lists of existing standards and test methods promulgated by various Government and non-Government standardizing groups, many of whose listings are described in this Chapter and from a study of specifications relating to plastics. Standardized test methods which constitute standardization documents on their own are covered, as are test methods which constitute only parts of material specifications. The citations are presented in alphabetical order, by test method subject rather than by material tested.

B-2.1.3 General Services Administration (GSA), Federal Supply Service

B-2.1.3.1 Index of Federal Specifications and Standards

This index provides general information on the Federal Standardization Document System, how to use the Index, and how to obtain Federal Standardization Documents. Tables of alphabetical listings are given for Federal and Interim Federal Specifications, Federal and Interim Standards, and Federal Handbooks. Also given are numerical listings for the same sources and also for the Federal Qualified Product Lists. Other tables include Federal Supply Classification (FSC) listings, and Federal Specifications and Standards cancelled or superseded during the previous year. Finally, a complete list of specifications and standards cancelled and superseded

with an indication of available QPL's through the previous year is given.

This index is for sale by the Superintendent of Documents at \$7.50 a year.

B-2.1.3.1.1 Federal Specifications

Federal Specifications are specifications promulgated by GSA for mandatory use by all Federal agencies, which describe the essential and technical requirements for items, materials, or services used by, or for partial use in, two or more Federal agencies, including the procedures for determining that the requirements have been met. These documents closely resemble Military Specifications.

Federal Specifications are designated by an identification system consisting of three parts, namely:

1. The first part is comprised of from one to three capital letters identifying the Federal procurement group to which the items belong.

2. The second part is a single letter which formerly designated the first letter of the specification title. (This letter is no longer significant.)

3. The third part is the serial number determined by its alphabetical location within the procurement group. Thus, L-P-395B covers "Plastic Molding (and Extrusion) Material, Nylon, Glass Fiber Reinforced".

B-2.1.3.1.1.1 Interim Federal Specifications

These are potential Federal Specifications issued in interim form for optional use by all Federal agencies when there is an immediate need and insufficient time to process the specification through concerned departments. These are designated in the same manner as Regular Federal Specifications, except that two zeros precede the serial number, and in parentheses after the serial number there is a code giving the agency responsible for the actual development and preparation of the specification.

B-2.1.3.1.1.2 Emergency Specifications

These specifications are designated in the same manner as Regular Federal Specifications, except that one zero precedes the serial number.

B-2.1.3.1.2 Federal Standards

These standards are promulgated by GSA for

mandatory use by all Federal agencies. They establish engineering and technical limitations and applications for items, materials, processes, methods, designs, and engineering practices.

Federal Standards are of five types:

1. Supply Standards
2. Test Method Standards
3. Material Standards
4. Engineering Standards
5. Procedural Standards.

The Test Method Standards appear as large compilations of widely coordinated test methods covering many different product or commodity areas. They adopt ASTM Methods to a great extent. This type of standard reflects agreement and uniformity between Government, suppliers, and industrial users of standard test methods. The individual standards involving test methods are designated as Federal Test Method Standards, and the designations incorporate the words "Test Methods".

B-2.1.4 National Aeronautics and Space Administration (NASA)

NASA specifications and standards have a more limited field of interest than military and Federal standardization documents.

B-2.1.4.1 NASA Specifications and Standards (NASA SP-9000)

This volume assembles in one publication an up-to-date listing of all specifications and standards originated by NASA, its Centers, and the Jet Propulsion Laboratory (JPL). It is arranged in three sections:

1. Section 1 is a listing of specifications and standards displayed by the alpha-numeric designation assigned by the originating organizations.

2. Section 2 is a subject index containing the significant terms in the titles of those specifications and standards containing that term. The titles are followed by the alpha-numeric designation and the source code.

3. Section 3 is an Originator Index. The specifications and standards are grouped by the NASA Center or origin. Only specifications and standards originated by NASA are included in this document. Contractor-generated specifications and standards which NASA may use from time to time are not included.

This document is available to organizations

registered with NASA to receive documents without charge through the NASA Scientific and Technical Information Facility, P.O. Box 33, College Park, MD 20740. Others may purchase copies from the National Technical Information Service at \$3.00.

B-2.1.4.2 Marshall Space Flight Center (MSFC) Specifications, Standards, and Procedures – Microfiche Reference File Index

This Index has been prepared to identify information contained on microfiche in the A&PS-MS-D Documentation Repository. It is divided into two sections:

1. Section I is a listing by document number in numerical sequence.
2. Section II is an alphabetical listing by title.

This Index is prepared by Hayes International Corp. and is published by Documentation Repository Dev. Management Services Office, MSFC.

B-2.1.4.3 George C. Marshall Space Flight Center Technical Specification Listing (MSFC-TSL-488B)

This document identifies the specifications and standards by user and subject; provides a brief scope of the document listed; and delineates pertinent use data (limitations, unique characteristics, etc.) relative to multiapplication technical specifications used by design and procuring activities of MSFC and its associated contractors. It consists of three sections:

1. Section I. Introduction
2. Section II. Technical Specification Listing
3. Section III. Specification Indices – which include a Specification Category Index, a Subject Index, and a Numerical Index.

B-2.1.4.4 George C. Marshall Space Flight Center Specifications and Standards for Space Systems and Related Equipment

This manual has been published to provide the MSFC with a means of realizing performance, cost, or schedule benefits through the use of approved design standards and material, process, and parts specifications which establish requirements for system/equipment definition and acquisition. The manual is arranged in a general sec-

tion and four annexes. Annex A contains the basic specifications and standards applicable to space systems and ground support equipment (GSE). Annex B contains documentation unique to GSE. Annexes C and D contain contract management publications and information publications, respectively.

B-2.1.4.5 Manned Spacecraft Center Nonmetallic Materials Design Guidelines and Test Data Handbook (MSC-02681 Revision B)

This document provides information on the selection of nonmetallic materials for application in manned spacecraft. Offgassing and combustion test requirements, test data, and the interpretation of test results are included. In addition, the document contains the latest Manned Spacecraft Center criteria for the selection of nonmetallic materials based on flammability and offgassing requirements. This is not a standardization document, but it will be of considerable interest to those involved with standardization of plastics. Its distribution is restricted to need-to-know recipients by NASA.

B-2.1.4.6 Office of Manned Space Flight, NASA Headquarters, NHB 8060.1, Flammability, Odor, and Offgassing Requirement and Test Procedures for Materials in Environments That Support Combustion

This document is issued to establish uniform material evaluation and control criteria for all materials that are under consideration for use in and around manned spacecraft during flight and test operations. The document provides:

1. Standard requirements for control of flammability, odor, and offgassing of materials to be used in the design and development of manned space vehicles
2. Guidelines and directions for material selection
3. Testing procedures for the candidate materials used in and around space vehicles during flight and test operations.

It is available from the Superintendent of Documents at \$1.00.

B-2.1.5 Rural Electrification Administration (REA)

This agency is a unit of the United States

Department of Agriculture. It issues a number of specifications involving telephone equipment installation, many of which involve plastics. Its mission is not listed in the NBS Directory, nor are its specifications tabulated in the World Index of Plastics Standards and the DODISS. Its specifications and standards are listed in the Current REA Publications—REA Telephone Borrowers—and contain specifications known to involve plastics and elastomers. REA Specifications are organized similar to Military and Federal Specifications.

B-2.2 NON-GOVERNMENT SOURCES

B-2.2.1 American National Standards Institute (ANSI)

This is a nonprofit organization with members from national trade, technical and professional groups, industry, Government agencies and departments, consumer groups, and similar organizations. The Institute serves as the national clearinghouse for standards and provides the machinery for developing and approving standards which are supported by a national consensus. Standards approved by the Institute (formerly called USA Standards) are now called American National Standards. The American National Standards Institute, Inc., is located at 1430 Broadway, New York, NY 10018. A copy of the current ANSI catalog is available free of charge.

The American National Standards listings also include cross-referencing to ASTM standards; the number designations of which are listed after the titles. A subject index to titles of Standards and International Specifications (including ISO) is published at the end of the Catalog.

Every two weeks the Institute publishes the *ANSI Reporter* and *Standards Action*. The *Reporter* is a newsletter describing the Institute's major activities on both the national and international levels. *Standards Action* solicits comments on standards that are being developed and lists those which have recently been approved or revised. *Standards Action* and the *Reporter* are available to nonmembers on a subscription basis.

B-2.2.2 International Organization for Standardization

ANSI is the United States member of the International Organization for Standardization (ISO), which consists of the national standards bodies of

70 countries. The United States' viewpoints to be presented in the technical work of the ISO are developed through a committee specially organized as a USA Technical Advisory Group for an ISO Technical Committee. The work of the ISO technical committees results eventually in ISO Standards which may be embodied in the national standards of the ISO's Member-Bodies. Many earlier Recommendations are being transformed into Standards.

ISO published several information documents which are described in the ANSI Catalog. Of interest is the ISO Catalog, which contains a full list of ISO Recommendations (and Standards) classified according to subject and number. The Catalog is issued annually, and a supplement listing revisions and new standards is published at three-month intervals. The cost is \$9.00.

Through an exchange system with the national standards bodies of other countries, ANSI has available national standards and catalogs of national standards of many countries. Most catalogs issued by other countries, as well as most standards, are available only in the language of origin.

B-2.2.3 American Society for Testing and Materials (ASTM)

The ASTM is the world's largest source of voluntary consensus standards. The society operates through technical committees representing prescribed fields of interest with membership from industry and government.

The standards are published in both collective book form and in separate pamphlet form. The Annual Book of ASTM Standards is published yearly in 47 volumes called "Parts". Standards can be located by subject or number from the Content Listings in the front of each book. Of interest are Parts 34 and 36, which deal with plastics, and Part 48, the index of all standards. Prices of each part vary. At present Parts 34, 35, 36, and 48 sell for \$18.00, \$31.00, \$24.00 and \$4.00, respectively. Individual standards in lots less than 50 may be purchased by coupon only. A five-coupon book is available at \$6.00 and a 25-coupon book at \$30.00. Orders should be directed to ASTM, 1916 Race Street, Philadelphia, PA 19103.

B-2.2.4 National Electrical Manufacturers' Association (NEMA)

This is a trade association of manufacturers of

equipment and apparatus for the generation, transmission, distribution, and utilization of electric power. NEMA may be considered an aggregate of product Sections. Each Section represents a group of manufacturers of certain classes of products such as Conduits, Ducts, and Fittings; Insulating Materials; and Wires and Cables. Sections with related interests are organized into Divisions.

NEMA has published separate standards publications in a number of classifications. A considerable amount of NEMA standardization activity is in cooperation with other organizations engaged in standardization, such as ASTM, Edison Electrical Institute, NFPA, Underwriters Laboratories, IEEE, and other associations, laboratories, or Government bodies.

B-2.2.5 Society of Automotive Engineers (SAE)

B-2.2.5.1 SAE Handbook

The SAE carries on technical standardization work for the motor vehicle, aircraft, airline, space vehicles, farm tractor, earth moving, and road-building machinery, and other manufacturing industries using internal combustion engines. The standards of the SAE are published annually in the SAE Handbook, except for the standards of the aerospace industry, which are published in looseleaf form as Aerospace Materials Specifications (AMS).

The society's standardization work is carried out under the general direction of an SAE Technical Board and technical committees. The technical committee activities also include active advisory cooperation with the Armed Forces and numerous other Federal and State government agencies. The SAE is active in international standardization and sponsors several US National Committees for ISO projects under the auspices of ANSI. In addition, many SAE standards have found international usage by being voluntarily adopted by foreign industry or government bodies.

All standards, specifications, and reports developed by the society are made available for industry, government, or other usage on a voluntary basis. SAE standards are recognized in government publications as sources for establishing minimum technical requirements in areas where government regulatory control has been established.

Standardization documents are published by

SAE in a handbook available at 2 Pennsylvania Plaza, New York, NY 10001, at \$40.00. A few of these are also ASTM standards. In those cases, ASTM makes this recognition in the upper right-hand corner of the first page of their standards, just as with ANSI.

B-2.2.5.2 SAE Aerospace Materials Specifications (AMS)

The standards and specifications published by SAE for the aerospace industry are issued in looseleaf form. Individual specifications are sold at \$3.00 each and are listed in the current AMS catalog.

The index of AMS Specifications is available from Society of Automotive Engineers, Inc., Department 010, 2 Pennsylvania Plaza, New York, NY 10001, at \$66.00.

Aerospace Materials Specifications are also listed in the DODISS. Titles and AMS numbers are given for many of the AMS specifications under "Identification of Materials Specifications, Test Methods and Standards".

B-2.2.6 Underwriters' Laboratories (UL)

The Underwriters' Laboratories has its main office at 207 East Ohio Street, Chicago, IL 60611; and laboratories at Chicago and Northbrook, IL; Melville, Long Island, NY; and Santa Clara, CA. UL is an organization established to maintain and operate laboratories for the examination and testing of devices, systems, and materials.

The requirements of a UL standard are so stated that, if correctly applied, there is no discrimination between the products of two or more manufacturer-submitters. They are published so that others may know the basis for the Laboratories' opinions, and the standards must necessarily justify the opinions.

A number of Federal Specifications covering materials or appliances of classes which are under the supervision of Underwriters' Laboratories recognize the Laboratories' UL label as compliance with the applicable requirements and standards. In its work with standardization, the UL cooperates with many other organizations such as ANSI, NFPA, and ASTM.

B-3 LIST OF PERTINENT DOCUMENTS

The following is a list of documents pertaining

to short fiber glass-filled thermoplastics:

1. *Plastic Molding Material, Acetal Glass Fiber Reinforced* (1970), MIL-P-46137 (1)

2. *Plastic Molding and Extrusion Material, Polyphenylene Oxide, Modified Glass Fiber Reinforced*, MIL-P-46131

3. *Molding Plastic, Polyamide Resin (Nylon) Glass-Fiber Filled and Molded Polyamide Resin Glass-Fiber Filled Plastic Parts*, MIL-M-19887

4. *Plastic Molding Material, Polycarbonate, Glass Fiber Reinforced*, MIL-P-81390

5. *Plastic Molding Material Polypropylene Glass Fiber Reinforced*, MIL-P-46109B

6. *Plastic Molding Material, Polystyrene Glass Fiber Reinforced*, MIL-P-21347C

7. *Plastic Molding Material, Polyterephthalate Thermoplastic Glass Fiber Reinforced*, MIL-P-46161

8. *Plastic Methods of Testing*, MIL-P-43398 and FED-STD-406

9. *Plastic Sheet, Flexible, Reinforced (Cellulose Acetate)*, L-P-1196

10. *Plastic Molding Material, Polyamide (Nylon), Glass Fiber Filled*, L-P-395

11. *Nylon Molding Material Glass Filled* (1964), L-P-395B

12. *Plastic Molding and Extrusion Material, Cellulose Acetate Butyrate*, L-P-349C

13. *Plastic Compound, Molding and Extruding, Polyphenylene Oxide Resin, Glass-Filled Modified*, WS 6268

14. *Plastic Compound, Molding and Extruding, Polycarbonate Resin, Glass Reinforced, Procurement of*, WS 6136

15. *Plastic, Fluorocarbon, Glass Fiber Filled, Description and Requirement*, WS 4145

16. REA Bull. 345-49, *Specification for Fiberglass Buried Terminal Housings* (PE-51)

17. *Tensile Properties of Glass Fiber Strands, Yarns, and Rovings Used in Reinforced Plastics*, ASTM D 2343

18. *Specifications for Reinforced and Filled Nylon Molding and Extrusion Materials* (1970), ASTM D 2897

19. *Reinforced Polycarbonate Injection Molding and Extrusion Materials*, ASTM D 2848

20. *Reinforced and Filled Polystyrene, Styrene-Acrylonitrile and Acrylonitrile-Butadiene-Styrene for Molding and Extrusion*, ASTM D 3011

21. *Glass Reinforced Acetal Parts for Molding and Extrusion*, ASTM D 2948.

REFERENCE

1. Arthur H. Landrock and Norman E. Beach, Chapter 11, "Commercial and Government Specifications and Standards", *Handbook of Plastics and Elastomers*, edited by Charles Harper, McGraw-Hill, New York, NY, 1975.

GLOSSARY

- Adherend.** A body which is held to another body by an adhesive.
- Adhesion.** The state in which two surfaces are held together at an interface by forces or interlocking action or both.
- Adhesiveness.** The property defined by the adhesion stress $A=F/S$ where F is the perpendicular force to the glue line and S its surface. It is expressed in newtons per square millimeter.
- Aging.** The effect, on materials, of exposure to an environment for an interval of time; the process of exposing materials to an environment for an interval of time.
- Air Locks.** Surface depressions on a molded part, caused by trapped air between the mold surface and the plastics material.
- Air Vent.** Small outlet, to prevent entrapment of gases.
- Alloy.** Composite material made by blending polymers or copolymers with other polymers or elastomers under selected conditions.
- Anisotropic.** Exhibiting different properties when tested along axes in different directions. (Anisotropy)
- Antistatic Agents.** Agents which, when added to the molding material or applied on the surface of the molded object, make it less conductive (thus hindering the fixation of dust).
- Arc Resistance.** The total time in seconds that an intermittent arc may play across a plastic surface without rendering the surface conductive.
- Aspect Ratio.** The ratio of length-to diameter of a fiber.
- Automatic Mold.** A mold that repeatedly goes through the entire molding cycle, including ejection, without human assistance.
- Automatic Press.** A hydraulic press for molding or which operates continuously, being controlled mechanically, electrically, hydraulically or by a combination of any of these methods.
- Back Pressure.** Resistance of a material, because of its viscosity, to continued flow when the mold is closing.
- Barcol Hardness.** A hardness value obtained by measuring the resistance to penetration of a sharp steel point under a spring load. This instrument, called the Barcol Impressor, gives a direct reading on a 0-100 scale.
- Binder.** The resin or cementing constituent of a plastic compound which holds the other components, i.e., glass fibers, together.
- Bond Strength.** The amount of adhesion between bonded surfaces; a measure of the stress required to separate a layer of material from the base to which it is bonded.
- Boss.** Protuberance on a plastic part designed to add strength, to facilitate alignment during assembly, to provide for fastening, etc. It may be solid, hollow, or have molded-in inserts.
- Bottom Plate.** A steel plate fixed to the lower section of a mold. It is often used to join the lower section of the mold to the platen of the press.
- Breaker Plate.** A perforated plate located at the rear of the die in an extruder. It supports the screens that prevent foreign particles from entering the die. Also used without screens in injection-molding nozzles to improve distribution of color particles in the melt.
- Breaking Extension ϵ_B .** The elongation necessary to cause rupture of the test specimen. The tensile strain at the moment of rupture.
- Breaking Factor.** Breaking load divided by the original width of the test specimen, expressed in pounds per inch.
- Bubble.** A spherical, internal void; globule of air or other gas trapped within a plastic.
- Bulk Factor.** The ratio of the volume of a molding compound or powdered plastic to the volume of the solid piece produced therefrom; the ratio of the density of the solid plastic object to the apparent density of the loose molding powder.
- Cavity.** Depression in mold; the space inside a mold wherein a resin is poured; the female portion of a mold; that portion of the mold which encloses the molded article; which forms the outer surface of the molded article (often referred to as the die); *also*, the space between matched molds. (Depending on number of such depressions, molds are designated as Single-Cavity or Multiple-Cavity). The cavity plate accommodates the individual mold cavities, which can be separate assemblies mounted into the cavity plate or, in the case of a single-cavity mold, can be machined directly into the cavity plate itself.
- Charge.** The measurement or weight of plastic material used to load a mold at one time or during one cycle.
- Clamping Plate.** A mold plate fitted to the mold

- and used to fasten the mold to the machine.
- Clamping Pressure.** The pressure which is applied to the mold to keep it closed; in opposition to the fluid pressure of the compressed molding material.
- Clearance.** A controlled distance by which one part of an object is kept separated from another part.
- Coefficient of Elasticity,** The reciprocal of Young's modulus in a tension test.
- Coefficient of Expansion.** The fractional change in dimension of a material for a unit change in temperature. *Also*, "coefficient of thermal expansion".
- Coefficient of Friction.** A measure of the resistance to sliding of one surface in contact with another surface.
- Coefficient of Linear Expansion.** The change in length per unit length resulting from a one-degree rise in temperature.
- Coefficient of Thermal Expansion α .** The change in volume per unit volume produced by a one-degree rise in temperature.
- Collapsing Cores.** Collapsing cores are used for internally threaded parts, such as closures and large blind threaded holes. The cores consist of separate wedge-shaped parts. As the mold opens, the individual core sections collapse inward to clear the threads in the molded part.
- Compatibility.** The ability of two or more substances combined with each other to form a homogeneous composition of useful plastic properties; for example, the suitability of a sizing or finish for use with certain general resin types; nonreactivity or negligible reactivity between materials in contact.
- Composite.** A homogeneous material created by the synthetic assembly of two or more materials (a selected filler or reinforcing elements and compatible matrix binder) to obtain specific characteristics and properties. Composites are subdivided into classes on the basis of the form of the structural constituents: Laminar—Composed of layer or laminar constituents; Particulate—the dispersed phase consists of small particles; Fibrous—the dispersed phase consists of fibers; and Flake—the dispersed phase consists of flat flakes.
- Compression Mold.** A mold which is open when the material is introduced and which shapes the material by heat and by the pressure of closing. *Also* "compression molding".
- Compressive Modulus E_c .** Ratio of compressive stress to compressive strain below the proportional limit. Theoretically equal to Young's Modulus determined from tensile experiments.
- Compressive Strength.** The ability of a material to resist a force that tends to crush; the pressure load at failure of a shaped specimen divided by a cross-sectional area of the specimen, usually the original sectional area.
- Compressive Stress.** The compressive load per unit area of original cross section carried by the specimen during the compression test.
- Conductivity.** Reciprocal of volume resistivity; the conductance of a unit cube of the material.
- Contact Adhesive.** An adhesive which requires that the surfaces to be joined shall be no further apart than about 0.1 mm for satisfactory bonding.
- Copolymer.** A long-chain molecule formed by the reaction of two or more dissimilar monomers.
- Copolymerization.** The building up of linear or nonlinear macromolecules (copolymers) in which many monomers, possessing molecules having one or many double bonds, have located in every macromolecule of different size which constitutes the copolymerizate, following alternations which may be regular or not.
- Core.** Core pin or blade used to form a hole in a molded part; part of a complex mold that forms undercut parts, (cores are usually withdrawn to one side before the main sections of the mold open); a channel in a mold for circulation of heat-transfer media; the male half of the mold that normally forms the inside section of the part.
- Core Plate.** The plate that accommodates the core or cores.
- Coupling Agent.** Any chemical substance designed to react with both the reinforcement and matrix phases of a composite material to form or promote a stronger bond at the interface; a bonding link.
- Crazing.** Defects in a polymer which appear to be fine cracks and may extend in a network on or under the surface or through a layer of material. They are not cracks, but areas of lower-density, oriented polymer. This phenomenon usually occurs in the presence of an organic liquid or vapor, with or without the application of mechanical stress.
- Creep.** The change in dimension of a plastic under load over a period of time, not including the initial instantaneous elastic deformation. (Creep at room temperature is called "cold flow".)

- Critical Fiber Length ℓ_c .** The distance over which the fiber stress builds up, counting both fiber ends, is the critical fiber length. It is the minimum length of a fiber which can reach its fracture strength.
- Cycle.** The complete, repeating sequence of operations in a process or part of a process. In molding, the cycle time is the period (or elapsed time) between a certain point in one cycle and the same point in the next.
- Daylight.** The distance, in the open position, between the moving and fixed tables or the platens of a hydraulic press. In the case of a multi-daylight press, daylight is the distance between adjacent platens.
- Deep-Draw Mold.** A mold having a core which is long in relation to the wall thickness.
- Deflection Temperature Under Load.** The temperature at which a simple beam has deflected a given amount under load (formerly called heat distortion temperature).
- Deformation Under Load.** The dimensional change of a material under load for a specific time following the instantaneous elastic deformation caused by the initial application of the load. (*Also*, "cold flow" or "creep".)
- D-Glass.** A high boron content glass made especially for items requiring a precisely controlled dielectric constant.
- Dielectric.** A nonconductor of electricity; the ability of a material to resist the flow of an electrical current.
- Dielectric Constant ϵ .** The ratio of the capacity of a condenser having a dielectric material between the plates to that of the same condenser when the dielectric is replaced by a vacuum; a measure of the electrical charge stored per unit volume at unit potential.
- Dielectric Heating.** (Electronic Heating) The plastic to be heated forms the dielectric of a condenser to which is applied a high-frequency (20-80 MHz) voltage. Dielectric loss in the material is the basis.
- Dielectric Loss.** A loss of energy eventually showing through the rise in heat of a dielectric placed in an alternative electric field.
- Dielectric Loss Angle.** (Dielectric Phase Difference) The difference between 90 deg and the dielectric phase angle.
- Dielectric Loss Index.** A measure of a dielectric loss defined by the product of the power factor and the permittivity (dielectric constant).
- Dielectric Strength.** The average potential per unit thickness at which failure of the dielectric material occurs.
- Dimensional Stability.** Ability of a plastic part to retain the precise shape to which it was molded, or otherwise fabricated.
- Doctor Roll; Doctor Bar.** A device for regulating the amount of liquid material on the rollers of a spreader.
- Draft.** The taper or slope of the vertical surfaces of a mold designed to facilitate removal of molded parts.
- Draft Angle.** The angle made by the tangent to the surface in that point and the direction of ejection.
- Drape.** The ability of material to conform to an irregular shape.
- Dry Strength.** The strength of an adhesive joint determined immediately after drying under specified conditions or after a period of conditioning in the standard laboratory atmosphere.
- Ductility.** The extent to which a solid material can be drawn into a thinner cross section. The ability of a material to elongate without fracturing.
- Dwell.** A pause in the application of pressure to a mold, made just before the mold is completely closed, to allow the escape of gas from the molding material.
- Dynamic Modulus.** The ratio of stress to strain under vibratory conditions (calculated from data obtained from either free or forced vibration tests, in shear, compression, or elongation).
- Edge Stiffening.** The design treatment applied to unsupported edges to prevent warping or bowing.
- Edgewise.** Refers to the cutting of specimens and to the application of load. The load is applied edgewise when it is applied to the edge of the original sheet or specimen. For compression-molded specimens of square cross section, the edge is the surface parallel to the direction of motion of the molding plunger; for injection-molded specimens of square cross section, this surface is selected arbitrarily.
- E-Glass.** A borosilicate glass; the type most used for glass fibers for reinforced plastics; suitable for electrical composites because of its high resistivity. (*Also* called "electric glass").
- Ejection.** The process of removing a molding from the mold impression; by mechanical means, by hand, or by the use of compressed air.
- Ejection Plate.** A metal plate used to operate ejector pins or ejector sleeves; designed to ap-

ply a uniform pressure to them in the process of ejection.

Ejection Ram. A small hydraulic ram fitted to a press for the purpose of operating ejector pins.

Ejector Pins. Ejector pins are mounted on an ejector plate and extend through the mold to the core or cavity molding surface. The pins are activated by the movement of the ejector plate, which is tied in with the injection press knockout system. When the mold opens (normally during the last part of mold opening, or stroke), the ejector plate pushes the ejector pins forward, extending them through the mold, thus forcing the part off the core or out of the cavity.

Elastic Deformation. That part of the total strain in a stressed body which disappears upon removal of the stress.

Elasticity. That property of a material by virtue of which it tends to recover its original size and shape after deformation. If the strain is proportional to the applied stress, the material is said to exhibit Hookean, or ideal, elasticity.

Electroformed Molds. A mold made by electroplating metal on the reverse pattern on the cavity.

Elongation. Deformation caused by stretching; the fractional increase in length of a material stressed in tension. (When expressed as percentage of the original gage length, it is called percentage elongation.)

Elongation at Break. Elongation recorded at the moment of rupture of the specimen, often expressed as a percentage of the original length.

End. A strand of roving consisting of a given number of filaments gathered together. (The group of filaments is considered an "end" or strand before twisting; a "yarn" after twist has been applied); an individual warp yarn, thread, fiber, or roving.

End Count. An exact number of ends supplied on a ball or roving.

Engineering Plastic (colloq). Plastics suited for engineering design; e.g., gears, structural members.

Environmental Stress Cracking. The susceptibility of a thermoplastic to crack or craze under influence of chemical treatment and or mechanical stress.

Fabricating, Fabrication. The manufacture of plastic products from molded parts, rods, tubes, sheeting, extrusions, or other form by

appropriate operations such as punching, cutting, drilling, and tapping. Fabrication includes fastening plastic parts together or to other parts by mechanical devices, adhesives, heat sealing, or other means.

Fatigue. The failure or decay of mechanical properties after repeated applications of stress. (Fatigue tests give information on the ability of a material to resist the development of cracks which eventually bring about failure as a result of a large number of cycles.)

Fatigue Strength. The maximum cyclic stress a material can withstand for a given number of cycles before failure occurs; the residual strength after being subjected to fatigue.

Fiber Diameter. The measurement (expressed in hundred-thousandths) of the diameter of individual filaments.

Fiberglass. 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 in.); a chopped fiber is a glass fiber of relatively short length of very small cross section.

Fiber Orientation. Fiber alignment in a composite where the majority of fibers are in the same direction, resulting in a higher strength in that direction.

Filaments. Individual glass fibers of indefinite length, usually as pulled from a stream of molten glass flowing through an orifice of the bushing. In the operation, a number are gathered together to make a strand or end of roving or yarn.

Filament Weight Ratio. In composite material, the ratio of filament weight to total weight of the composite.

Filler. A relatively inert material added to a plastic mixture to reduce cost, to modify mechanical properties, to serve as a base for color effects, or to improve the surface texture.

Fillet. A rounded filling of the internal angle between two surfaces of a plastic molding.

Finish. A material applied to the surface of glass fibers used to reinforce plastics and intended to improve the physical properties of such reinforced plastics over that obtained using reinforcement without finish.

Flame Resistance. Ability of a material to extinguish flame once the source of heat is removed.

- Flame Retardants.** Certain chemicals which are used to reduce or eliminate a tendency of a resin to burn.
- Flame Retarded Resin.** A resin which is compounded with certain chemicals to reduce or eliminate its tendency to burn.
- Flammability.** Measure of the extent to which a material will support combustion.
- Flash.** That portion of the charge which flows from or is extruded from the mold cavity during the molding; extra plastic attached to a molding along the parting line. (It must be removed before the part is considered finished.)
- Flexural Modulus.** The ratio, within the elastic limit, of the applied stress on a test specimen in flexure to the corresponding strain in the outermost fibers of the specimen.
- Flexural Rigidity (Fibers).** A measure of the rigidity of individual strands or fibers; the force couple required to bend a specimen to unit radius of curvature.
- Flexural Strength.** The resistance of a material to being broken by bending stresses; the strength of a material in bending, expressed as the tensile stress of the outermost fibers of a bent test sample at the instant of failure. (With plastics, this value is usually higher than the straight tensile strength.)
- Force.** The male half of the mold which enters the cavity, exerting pressure on the resin and causing it to flow (also referred to as "punch"); either part of a compression mold; top force and bottom force.
- Friction Welding.** A method of welding thermoplastic materials in which the heat necessary to soften the components is provided by friction.
- Gate.** In injection and transfer molding, the orifice through which the melt enters the cavity. Sometimes the gate has the same cross section as the runner leading to it; often, it is severely restricted.
- Glass.** An inorganic product of fusion which has cooled to a rigid condition without crystallizing. (Glass is typically hard and relatively brittle, and has a conchoidal fracture.)
- Glass Fiber.** A glass filament that has been cut to a measurable length. Staple fibers of relatively short length are suitable for spinning into yarn.
- Glass Filament.** A form of glass that has been drawn to a small diameter and extreme length. (Most filaments are less than 0.005 in. in diameter.)
- Glass Finish.** A material applied to the surface of a glass reinforcement to improve its effect upon the physical properties of the reinforced plastic. (Also "bonding agent".)
- Glass, Percent by Volume.** The product of the specific gravity of a laminate and the percent glass by weight, divided by the specific gravity of the glass.
- GRTP.** Glass fiber reinforced thermoplastic; a general term covering any type of discontinuous glass fiber reinforced thermoplastic material.
- Guide Pin.** A pin which guides mold halves into alignment on closing.
- Hardness.** The resistance to surface indentation usually measured by the depth of penetration (or arbitrary units related to depth of penetration) of a blunt point under a given load using a particular instrument according to a prescribed procedure.
- Heat Distortion Point.** The temperature at which a standard test bar deflects under a stated load.
- Heated Tool Welding.** A bonding method whereby the surfaces to be joined are placed against a heated metal plate, then pressed together until the fused joint has cooled. Applicable primarily when joint faces are flat.
- Heat Endurance.** The time of heat aging that a material can withstand before failing a specific physical test.
- High-Frequency Heating.** The heating of materials by dielectric loss in a high-frequency electrostatic field. The material is exposed between electrodes and is heated quickly and uniformly by absorption of energy from the electrical field.
- Hobbing.** In mold making the process which takes a hardened steel replica (hob) of the plastic part and under high pressure forces it into a soft iron block.
- Hot Gas Welding.** A technique of joining thermoplastic materials (usually sheet) whereby the materials are softened by a jet of hot air from a welding torch and joined together at the softened points. Generally a thin rod of the same material is used to fill and consolidate the gap.
- Hot Wire Welding.** A bonding method whereby a resistance wire is placed between the surfaces to be joined; the heat generated melts the adjacent surfaces enough to effect a fused bond. Exposed ends of the resistance wire can then be snapped off.

Hydraulic Press. A press in which the molding force is created by the pressure exerted on a fluid.

Hydromechanical Press. A press in which the molding forces are created partly by a mechanical system and partly by a hydraulic system.

Hydrophilic. Capable of adsorbing or absorbing water.

Hydrophobic. Capable of repelling water.

Hygroscopic. Capable of adsorbing and retaining atmospheric moisture.

Impact Strength. The ability of a material to withstand shock loading; the work done in fracturing a test specimen in a specified manner under shock loading.

Impact Tests. The impact test measures the energy necessary to fracture a specified specimen by an impulse load. In the Izod Impact test, a standard notched test specimen is struck and fractured by a heavy pendulum, released from a known height, at the nadir of its swing. From a knowledge of the mass of the pendulum and the difference in the initial and final heights, the energy absorbed in fracture is calculated. A standard ASTM notch is: 45 deg included angle, 0.010 in. radius at the tip of the notch, and a notch depth of 0.100 in. in a 0.500-in. specimen. Results are reported in foot-pounds or ergs or foot-pounds per inch notch width.

Infrared. Part of the electromagnetic spectrum between the visible light range and the radar range. Radiant heat is in this range, and infrared heaters are much used in GRTP processing.

Inhibitor. A substance which retards a chemical reaction; used in certain types of monomers and resins to prolong storage life.

Injection Molding. The method of forming a plastic to the desired shape by forcing the heat-softened plastic into a relatively cool cavity under pressure.

Injection Ram. The ram which applies pressure to the plunger in the process of injection molding or transfer molding.

Insert. An integral part of a plastics molding consisting of metal or other material which may be molded into position or pressed into the molding after the molding is completed.

Insulation Resistance. The electrical resistance between two conductors or systems of conductors separated only by insulating material; the ratio of the applied voltage to the total current

between two electrodes in contact with a specified insulator.

Insulator. A material of such low electrical conductivity that the flow of current through it can usually be neglected. Similarly, a material of low thermal conductivity.

Interface. The junction point or surface between two different media; on glass fibers, the contact area between glass and sizing or finish; in a composite, the contact area between the reinforcement and the matrix resin.

Interlaminar Shear Strength. The maximum shear stress existing between glass reinforcement and matrix material.

Intrinsic Viscosity. A solution viscosity measurement directly related to polymer molecular weight.

Joint. The location at which two adherends are held together with a layer of adhesive, the general area of contact for a bonded structure.

Joint, Butt. A type of edge joint in which the edge faces of the two adherends are at right angles to the other faces of the adherents.

Joint, Edge. A joint made by bonding the edge faces of two adherends.

Joint, Lap. A joint made by placing one adherend partly over another and bonding together the overlapped portions.

Joint, Scarf. A joint made by cutting away similar angular segments of two adherends and bonding them with the cut areas fitted together.

Kirkosite. An alloy of aluminum and zinc. Used with some success to cast molds.

Land. The portion of a mold which provides the separation or cutoff of the flash from the molded article; in the screw of an extruder, the bearing surface along the top of the flights; in an extrusion die, the surface parallel to the flow of material; in a semipositive or flash mold, the horizontal bearing surface; in a two-piece mold, a platform built up to the split line.

Land Area. The whole of the area of contact, perpendicular to the direction of application of pressure of the seating faces of a mold; those faces which come into contact when the mold is closed.

Landed Force. A force with a shoulder which seats on land in a landed positive mold.

L/D Ratio. A term used to denote the ratio of an extrusion or injection machine screw length to the screw diameter.

Linear Expansion. The increase of a planar di-

- mension, measured by the linear elongation of a sample in the form of a beam which is exposed to two given temperatures.
- Line Pressure.** The pressure under which an air or hydraulic system operates.
- Loss Modulus.** A damping term describing the dissipation of energy into heat when a material is deformed.
- Low-Pressure Molding.** The distribution of relatively uniform low pressure (200 psi or less) over a glass-reinforced thermoplastic compound, with or without application of heat from external source, to form a structure possessing definite physical properties.
- Machine Screw.** A blunt-ended screw with a standardized thread and a head that may be flat, round, fillister, or oval and may be slotted or constructed for wrenching.
- Matched Metal Molding.** A reinforced plastics manufacturing process in which matching male and female metal molds are used (similar to compression molding) to form the part.
- M-Glass.** A high beryllia content glass designed especially for high modulus of elasticity.
- Micron.** One micron = 0.001 mm = 0.00003937 in.
- Mil.** The unit used in measuring the diameter of glass fiber strands, etc. (1 mil = 0.001 in.).
- Modulus of Elasticity.** The ratio of the stress or load applied to the strain or deformation produced in a material that is elastically deformed. If a tensile strength of 2000 pounds per square inch results in an elongation of one percent, the modulus of elasticity is 2000 divided by 0.01, or 200,000 pounds per square inch (Young's modulus).
- Moisture Absorption.** The pickup of water vapor from air by a material. It relates only to vapor withdrawn from the air by a material and must be distinguished from water absorption, which is the gain in weight due to the take-up of water by immersion.
- Moisture Vapor Transmission.** A rate at which water vapor will pass through a material at a specified temperature and relative humidity (g•mil/24 h•100 in.).
- Mold.** The cavity or matrix into or on which the plastic composition is placed and from which it takes form; to shape plastic parts or finished articles by heat and pressure; the assembly of all the parts that function collectively in the molding process.
- Molding.** The shaping of a plastic composition within or on a mold, normally accomplished under heat and pressure; sometimes used to denote the finished part.
- Molding Compounds.** Plastics in a wide range of forms to meet specific processing requirements. Granules or pellets are popular forms.
- Molding Cycle.** The period of time occupied by the complete sequence of operations on a molding press requisite for the production of one set of moldings; the operations necessary to produce a set of moldings without reference to the time taken.
- Molding Powder.** Plastic material in varying stages of granulation, and comprising resin, filler, reinforcements, pigments, plasticizers, and other ingredients, ready for use in the molding operation.
- Molding Pressure.** The pressure applied to the ram of an injection machine or press to force the softened plastic completely to fill the mold cavities.
- Mold Plates.** A mold is made up of a number of separate steel plates; each performs a specific structural function in the operation of the mold. A mold can have from 2 to 10 or more plates.
- Mold-Release Agent.** A liquid or powder used to prevent sticking of molded articles in the cavity.
- Mold Shrinkage.** The immediate shrinkage which a molded part undergoes when it is removed from a mold and cooled to room temperature; the difference in dimensions, expressed in inches per inch between a molding and the mold cavity in which it was molded (at normal temperature measurement); the incremental difference between the dimensions of the molding and the mold from which it was made, expressed as a percentage of the dimensions of the mold.
- Monomer.** A simple molecule which is capable of reacting with like or unlike molecules to form a polymer; the smallest repeating structure of a polymer (mers); for addition polymers, this represents the original unpolymerized compound.
- Multiple-Cavity Mold.** A mold with two or more mold impressions, i.e., a mold which produces more than one molding per molding cycle.
- Nominal Thickness.** Nominal thickness is the overall design thickness of most or all sections of a part.
- Nonpolar.** Having no concentration of electrical charges on a molecular scale; thus, incapable of significant dielectric loss. Examples among resins are polystyrene and polyethylene.

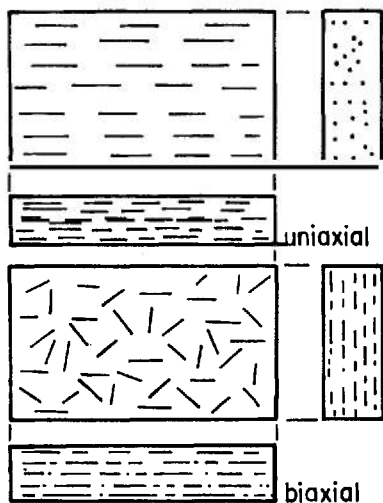
Notch Sensitivity. The extent to which the sensitivity of a material to fracture is increased by the presence of a surface inhomogeneity such as a notch, a sudden change in section, a crack or a scratch. Low notch sensitivity is usually associated with ductile materials and high notch sensitivity with brittle materials.

Nozzle. The hollow, cored, metal nose screwed into the extrusion end of the heating cylinder of an injection machine or a transfer chamber (where this is a separate structure). A nozzle is designed to form, under pressure, a seal between the heating cylinder or the transfer chamber and the mold.

Orange Peel. An uneven surface somewhat resembling that of an orange peel; said of injection moldings that have unintentionally rugged surfaces.

Organic. Designating or composed of matter originating in plant or animal life or composed of chemicals of hydrocarbon origin, either natural or synthetic.

Oriented Composite Materials. Materials whose reinforcements are aligned in a specific way. Oriented materials are anisotropic. Orientation can generally be divided into two classes: uniaxial and biaxial. Ideal uniaxial and biaxial orientations are illustrated below.



Parting Line. A mark on a mold piece where the sections of a mold have met in closing.

Peel Strength. Bond strength, in pounds per inch of width, obtained by peeling the joined surfaces.

Pinhole. A tiny hole in the surface of, or through, a plastic material; usually occurring in multiples.

Pin, Insert. A pin which keeps an inserted part (insert) inside the mold, by screwing or by friction; removed when withdrawing the object from the mold.

Plastic. A material that contains as an essential ingredient an organic substance of large molecular weight, is solid in its finished state, and, at some stage in its manufacture or its processing into finished articles, can be shaped by flow.

Plunger. A ram or piston used for the displacement of fluid or semifluid materials in injection- or extrusion-molding methods; also called piston, pommel, force, force plug, and pot plunger.

Polymer. A high molecular weight organic compound, natural or synthetic, whose structure can be represented by a repeated small unit, the monomer. Synthetic polymers are formed by addition or condensation polymerization of monomers. When two or more monomers are involved, the product is called a copolymer.

Power Factor. The cosine of the phase angle. Ratio of the dielectric constant E' to the absolute value of the complex dielectric constant ϵ^* .

Proportional Limit. The greatest stress which a material is capable of sustaining without deviation from proportionality of stress and strain (Hooke's law). It is expressed in force per unit area, usually in pounds per square inch.

Prototype. A model suitable for use in complete evaluation of form, design, and performance.

Prototype Mold. A simplified mold construction often made from a light metal casting alloy, such as aluminum, used to obtain information for the final mold and/or part design.

Radius. The term in mold making defines the curvature established between two intersecting surfaces. The more generous the radius, the better the flow of molding material and the less likelihood of "resin-rich" areas with low abuse resistance.

Ram Force. The total load applied by a ram, and numerically equal to the product of the line pressure and the cross-sectional area of the ram. It is normally expressed in tons.

Ram Travel. The distance the injection ram moves in filling the mold, in injection.

Reinforced Plastic. A plastic with strength properties greatly superior to those of the base resin, resulting from the presence of reinforcements imbedded in the composition.

Reinforcement. A strong inert material bonded

- into a plastic to improve its strength, stiffness, and impact resistance. Reinforcements are usually long fibers of glass, asbestos, sisal, cotton, etc., in woven or nonwoven form. To be effective, the reinforcing material must form a strong adhesive bond with the resin.
- Release Agent.** A material which is applied in a thin film to the surface of a mold to keep the resin from bonding to the mold.
- Resin.** In reinforced plastics, the material used to bind together the reinforcement material; the "matrix".
- Resin Content.** The amount of resin in a composite expressed as either a percent of total weight or total volume.
- Resin-Rich Area.** Space which is filled with resin and lacks reinforcing material.
- Resistivity.** The ability of a material to resist passage of electrical current either through its bulk or on a surface. The unit of volume resistivity is the ohm•cm; of surface resistivity, the ohm.
- Reverse Impact Test.** In which one side of a sheet of material is struck by a pendulum or falling object and the reverse side is inspected for damage.
- Rib.** A reinforcing member of a fabricated or molded part.
- Rivet.** A short rod with a head formed on one end; it is inserted through aligned holes in parts to be joined and the protruding end is pressed or hammered to form a second head.
- Rockwell Hardness Number.** A value derived from the increase in depth of an impression as the load on an indenter is increased from a fixed minimum value to a higher value and then returned to the minimum value. Indenters for the Rockwell test include steel balls of several specific diameters and a diamond cone penetrator having an included angle of 120 deg with a spherical tip having a radius of 0.2 mm. Rockwell hardness numbers are always quoted with a prefix representing the Rockwell scale corresponding to a given combination of load and indenter.
- Rotational Molding.** A method used to make hollow articles from plastic powders. The material is charged into a hollow mold capable of being rotated in one or two planes. The hot mold fuses the polymer after the rotation has caused it to cover all surfaces. The mold is then chilled and the product stripped out.
- Roving.** A collection of parallel strands or filaments assembled with or without intentional twist.
- Runner.** The channel that connects the sprue with the gate to the mold cavity.
- Screw Plasticating Injection Molding.** A molding technique in which the plastic is converted from pellets to a viscous melt by means of an extruder screw that is an integral part of the molding machine. Machines are either single-stage, in which plastication and injection are done by the same cylinder, or double-stage in which the material is plasticated in one cylinder and fed to a second for injection into a mold.
- Secant Modulus.** The ratio of total stress to corresponding strain at any specific point on the stress-strain curve. It is expressed in force per unit area, usually in pounds per square inch, and reported together with the specified stress or strain.
- Self-Extinguishing Resin.** A resin formulation which will burn in the presence of a flame but which will extinguish itself within a specified time after the flame is removed.
- Self-Tapping Screw.** A screw with a specially hardened thread that makes it possible for the screw to form its own internal thread in material when driven into a hole.
- S-Glass.** A magnesia-alumina-silicate glass, especially designed to provide very high tensile strength glass filaments.
- Shear.** An action or stress resulting from applied forces which causes or tends to cause two contiguous parts of a body to slide relative to each other in a direction parallel to their plane of contact.
- Shear, Interlaminar (ILS).** This is shear associated with reinforced plastics. Failure occurs in resin only at the mid plane of the composite.
- Shear Modulus G.** The ratio of shearing stress τ to shearing strain γ within the proportional limit of a material.
- Shore Hardness.** A method of determining the hardness of a plastic material. The device used consists of a small conical hammer fitted with a diamond point and acting in a glass tube. The hammer is made to strike the material under test and the degree of rebound is noted on a graduated scale. Generally, the harder the material the greater will be the rebound.
- Short Beam Shear Strength.** The interlaminar shear strength of a parallel fiber reinforced plastic material as determined by three-point

flexural loading of a short segment cut from a ring-type specimen.

Shrinkage. The relative change in dimension between the length measured on the mold when it is cold and the length on the molded object 24 h after it has been taken out of the mold.

Side Cores. Cores used to form undercuts or holes located perpendicular to the direction of mold openings.

Sink Mark. A shallow depression or dimple on the surface of an injection molded part due to collapsing of the surface following local internal shrinkage after the gate seals; an incipient short shot.

Size (Sizing). Any treatment consisting of starch, gelatine, oil, wax, or other suitable ingredient which is applied to glass fibers at the time of formation to protect the surface and aid the process of handling and fabrication, or to control the fiber characteristics. The treatment contains ingredients which provide surface lubricity and binding action but, unlike a finish, contains no coupling agent. Before final fabrication into a composite, the size is usually removed by heat-cleaning, and a finish is applied.

Sizing Content. The percent of the total strand weight made up by the sizing; usually determined by burning off the organic sizing ("loss on ignition").

Sleeve Plates. Steel plates located between the core and cavity plate and used for sleeve ejection. The sleeve plate itself can perform the ejection or can contain a number of separately mounted individual sleeves as used in multi-cavity molds.

Solvent Bonding. A bonding method whereby solvent is used to dissolve enough of the surfaces to be joined that they can be bonded under pressure. Choice of solvent depends on the polymer used. This method works best with the amorphous thermoplastic resin systems.

Solvent Resistance. The nonswelling of a material or the impossibility for it to be dissolved by the solvent in question.

Specification. A detailed description of the characteristics of a material or product and of the criteria which must be used to determine whether it is in conformity with the description.

Specific Gravity. The density (mass per unit volume) of any material divided by that of water

at a standard temperature, usually 4° C. Since water's density is nearly 1.00 g/cm³, density in g/cm³ and specific gravity are numerically nearly equal.

Specific Heat. The quantity of heat required to raise the temperature of a unit mass of a substance one degree under specified conditions.

Specific Stress (Fibers). The load divided by the mass per unit length of the test specimen.

Specimen. An individual piece or portion of a sample used to make a specific test; of specific shape and dimensions.

Spin Welding. A process of fusing two objects together by forcing them together while one of the pair is spinning until frictional heat melts the interface. Spinning is then stopped and pressure held until they are frozen together.

Split Mold. A mold in which the cavity is formed of two or more components held together by an outer chase. The components are known as splits.

Split-Ring Mold. A mold in which a split cavity block is assembled in a chase to permit the forming of undercuts in a molded piece. These parts are ejected from the mold and then separated from the piece.

Sprayed Metal Molds. Molds made by spraying molten metal onto a master until a shell of predetermined thickness is achieved. The shell is then removed and backed up with plaster, cement, casting resin, or other suitable material. Used primarily as a mold in sheet forming process.

Sprue. Feed opening provided in the injection mold; also the slug formed at this hole. Spur is a shop term for the sprue slug.

Sprue Bushing. In an injection mold, a hardened steel insert which contains the tapered sprue hole and has a suitable seat for making close contact with the nozzle of the injection cylinder.

Stiffness. The relationship of load and deformation; a term often used when the relationship of stress to strain does not conform to the definition of Young's modulus.

Strain E. Strain may have several definitions, which are dependent upon the system being considered. For small deformations, engineering strain is applicable and is the most common definition of strain. The quality called true strain is sometimes used in areas of plastic deformation.

1. Engineering strain E : The ratio of the change in length, ΔL of the same to its original length L_0 .
2. True strain ϵ_1 : The integral of the ratio of the incremental change in length to the instantaneous length of a plastically deformed sample; thus, the natural logarithm of the ratio of instantaneous length to original length of such a sample.

Strands. A primary bundle of continuous filaments (or slivers) combined in a single compact unit without twist. These filaments (usually 51, 102, or 204) are gathered together in the forming operations.

Strand Count. The number of strands in a roving.

Strand Integrity. The degree to which the individual filaments making up the strand or end are held together by the sizing applied.

Stress σ . Most commonly defined as "engineering stress", the ratio of the applied load P to the original cross-sectional area A_0 , i.e., $\sigma = P/A_0$. The "true stress" σ_t or instantaneous stress is sometimes used and is defined as the applied load P per instantaneous cross-sectional area A , i.e., $\sigma_t = P/A$.

Stress Concentration. The magnification of the level of an applied stress in the region of a notch, void, or inclusion.

Stress Concentration Factor. The ratio of the maximum stress in the region of a stress concentrator to the stress in a similar strained area without a stress concentrator.

Stress Corrosion. Preferential attack of areas under stress in a corrosive environment, where this factor alone would not have caused corrosion.

Stress-Crack. External or internal cracks in a plastic caused by tensile stresses less than that of its short-time mechanical strength. The stresses which cause cracking may be present internally or externally or may be combinations of these stresses.

Stress Relaxation. The decrease in stress under sustained constant strain.

Stress-Strain. Stiffness, expressed in pounds per square inch or newtons per square meter (pascal), at a given strain.

Stress-Strain Curve. Simultaneous readings of load and deformation, converted to stress and strain, are plotted as ordinates and abscissae, respectively, to obtain a stress-strain diagram.

Structural Bond. A bond that joins basic load-

bearing parts of an assembly. The load may be either static or dynamic.

Surface Resistivity (Electrical). The surface resistivity of a material is the ratio of potential gradient parallel to the current along its surface, to the current per unit width of surface. Surface resistivity is numerically equal to the surface resistance between opposite sides of a square of any size when the current flow is uniform.

Surface Treatment. A material applied to fibrous glass during the forming operation or in subsequent processes (i.e., size or finish).

Tensile Strength or Stress. The maximum tensile load per unit area of original cross section, within the gage boundaries, sustained by the specimen during a tension test. It is expressed as psi. Tensile load is interpreted to mean the maximum tensile load sustained by the specimen during the test, whether or not this coincides with the tensile load at the moment of rupture.

Thermal Conductivity. Ability of a material to conduct heat. The physical constant for quantity of heat that passes through unit cube of a substance in unit time when the difference in temperature of two faces is one degree.

Thermal Decomposition. Decomposition resulting from action by heat. It occurs at a temperature for which some components of the material are separating or associating together, with a modification of the macro- or microstructure.

Thermal Stress Cracking. Crazing and cracking of some thermoplastic resins which result from overexposure to elevated temperatures.

Thermoplastic. Capable of being repeatedly softened by increase of temperature and hardened by decrease in temperature; applicable to those materials whose change upon heating is substantially physical rather than chemical.

Toggle Action. A mechanism which exerts pressure developed by the application of force on a knee joint; used as a method of closing presses and applying pressure at the same time.

Top and Bottom Clamp Plates. Plates used for multicavity molds to provide a structural backing for the cores and/or cavities. They are mounted directly to the press plate.

Torpedo. A streamlined metal block placed in the path of flow of the plastic in the heating cylinder of extruders and injection-molding machines and used to spread the plastic into thin

layers and force it into contact with the heating areas.

Toughness. The energy required to break a material. This energy is equal to the area under the stress-strain curve.

Two-Plate Molds. Two-plate molds are those in which the part and the runner are ejected from the same opening in the mold.

Ultimate Tensile Strength. The ultimate or final stress sustained by a specimen in a tension test; the stress at moment of rupture.

Ultrasonic Bonding. A bonding method which is accomplished through the application of vibratory mechanical pressure at ultrasonic frequencies (20-40 Hz). Electrical energy is converted to ultrasonic vibrations through the use of either a magnetostrictive or piezoelectric transducer. The vibratory pressures at the interface in the bonding area develop localized heat losses which melt the plastic surfaces effecting the seal.

Undercut. A protuberance or indentation that impedes withdrawal from a two-piece, rigid mold; any such protuberance or indentation, depending on the design of the mold.

Viscosity. The property of resistance to flow exhibited within the body of a material, expressed in terms of relationship between applied shearing stress and resulting rate of strain in shear. Viscosity is usually taken to mean Newtonian viscosity, in which case the ratio of shearing stress to the rate of shearing strain is constant. In non-Newtonian behavior, which is the usual case with plastics, the ratio varies with the shearing stress. Such ratios are often called the "apparent viscosities," at the corresponding shearing stresses.

Voids. Gaseous pockets that have been trapped into a composite.

Volatiles. Material in a sizing or a resin formulation which is capable of being driven off as a vapor at room or slightly elevated temperature.

Volume Resistance. The volume resistance between two electrodes that are in contact with

or embedded in a specimen is the ratio of the direct voltage applied to the electrodes, to that portion of the current between them that is distributed through the volume of the specimen. Also, the electrical resistance between opposite faces of a 1-cm cube of insulating material, commonly expressed in ohm-centimeters.

Water Absorption. Ratio of the weight of water absorbed by a material to the weight of the dry materials.

Weathering. The exposure of plastics outdoors.

Weathering, Artificial. The exposure of plastics to cyclic laboratory conditions comprising high and low temperatures, high and low relative humidities, and ultraviolet radiant energy — with or without direct water spray — in an attempt to produce changes in their properties similar to those observed on long-time continuous exposure outdoors. The laboratory exposure conditions are usually intensified beyond those encountered in actual outdoor exposure in an attempt to achieve an accelerated effect.

Weld Lines. The line created by the fusion of material as it flows around an obstruction in the mold, such as a core pin, or insert. Generally, the weld line will be visible under magnification. It often will be mistaken for a hairline crack.

Yield Point. The first stress in a material, less than the maximum attainable stress, at which an increase in strain occurs without an increase in stress. Only materials that exhibit this unique phenomenon of yielding have a "yield point".

Yield Strength. The stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain; the lowest stress at which a material undergoes plastic deformation. Below this stress, the material is elastic; above it, viscous.

Young's Modulus. The ratio of tensile stress to tensile strain below the proportional limit.

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